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ROYAL AERONAUTICAL SOCIETY 1866

Journal

of

THE ROYAL AERONAUTICAL SOCIETY

SEPTEMBER 1955

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All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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Secretary's News Letter

September 1955.

THE FIFTH Anglo-American Aeronautical Conference is over. A Report of it will be given in the next issue of the Journal, so I shall not anticipate anything which may be said then.

That the Conference was a great success nobody will deny; it was a success from the technical viewpoint of the papers and discussions; it was more than a success in the way in which the friendliest of relationships were engendered. Everywhere the British delegates were received with overwhelming hospitality. Everyone was ready, willing and eager to act as hosts (and hostesses) on the slightest of excuses, and nothing was too much trouble. Everyone went out of his or her way to help in every way, and I'm sure I echo the thoughts of every delegate when I say thank you for the very many kindnesses which were received from *all* the Americans, without any discrimination in gender.

I should like to give my personal thanks to Mr. Paul Johnston, whose usual phrase seems to be "Think nothing of it"; to Miss Marjory Rodé, who contrived this and that for our benefit, to Mr. Bob Dexter, who lives up to his name and is a "right guy"; to big, genial Mr. Joe Maitan who beamed towering goodwill; to Mr. "Shrade" Shrader, the imperturbable; to Mr. Joe Ryan (no relation to the firm bearing the same name) whose flamboyant good nature gave everyone so much pleasure, and to Mr. "Robbie" Robischon, who must surely be the Prime Minister to "Davy Crockett, King of the Wild Frontier."

My list of benevolent personages is long—too long to be enumerated in detail—but to Mr. and Mrs. "Bob" Gross, the President of the Institute of the Aeronautical Sciences, to Mr. and Mrs. "Mac" McCarthy, Past President, to Mr. and Mrs. Arthur Raymond, and to Professor and Mrs. Nicholas Hoff, my wife and I would tell our appreciative thanks for their many thoughtful kindnesses.

On our first Sunday in Los Angeles we were not "organised", but quickly Mr. Johnston spoke to Mr. Robischon, and quickly, as if out of a hat, were produced Dr. and Mrs. Baillie Oswald, who were prepared to act as guides; need I say that our introduction to the famous Californian hospitality was all that could be asked. We were shown (at our request) the Pacific, and I produced the fatuous remark "I've seen the other side of it." We spent a very interesting and entertaining afternoon and evening, thanks to Baillie and Lucia Oswald.

Since I've returned home I have been asked about impressions of America in general, and California in particular.

For many years I have seen (in text books) drawings and diagrams of flyovers, freeways, clover leaves, but never seen one until I saw these on the American Continent. Traffic control impressed me also—Americans are supposed to be extremely individualistic and yet they, as pedestrians, cross at the end of the block, never against the red light. It appears to me that some such thing could be done in the United Kingdom. Give the pedestrian priority over the turning vehicle at the green light. "Wait! Walk!" and why not?

The building of aircraft in the open is, of course, only made possible by the climate, but what an aid to production!

I have forgotten the number of square miles in Los Angeles (any cab driver will tell you)—I have forgotten the number of cars in use in California, I have forgotten the mileage of the freeways—but I do not forget that Los Angeles is vast, that the number of cars is practically numberless, and that the freeways are lengthy. Los Angeles is no Jerusalem—I know nothing of its morals, I'm referring to the fact that it is not "compactly built together."

As well as Los Angeles we visited San Diego, where the sailors come from, and San Francisco, where they still have cable cars which, despite the fact that they appear to be well and truly over-laden, don't seem to pay. Speaking of pay, I do not know the pay of a cable-car driver, but whatever he is paid, it is not overmuch, for I've never seen a driver put so much energy into his work. He has to!

Some twenty-odd delegates spent the 4th July week-end in Yosemite National Park. The valley was only discovered during the latter part of the nineteenth century, but it has become very popular since.

The scenery is very lovely, the view from Glacier Point being superb. The mountains bound the narrow valley with vertical sides, and present a blank grey wall. To complement the magnificent waterfall, at night a "Fire Fall" is pushed over from Glacier Point for the wondersome awe of the tourist. Yosemite Park was well worth the visit, if only for the sight of Mama Bear and her two cubs wandering around the huts unconcernedly investigating.

We spent a few days in Seattle and visited Boeings. In Seattle some of the roads are so steep that the sidewalks (pavements) are ridged to give a foothold to the pedestrian.

From Seattle we went to Vancouver, crossed the Rockies by the C.N.R. Super Continental, and visited in turn Jasper, Edmonton, Winnipeg, Toronto, Ottawa

and Montreal, and throughout the breadth of Canada we were entertained by members of the Canadian Aeronautical Institute, for Mr. Charles Luttman, the C.A.I. Secretary, had informed all their Branches concerning our itinerary.

The C.A.I. is making rapid strides, and has now a membership of about 1,200, with Branches in Vancouver, Winnipeg, Toronto, Ottawa, and Montreal. The Council of the C.A.I. are to be congratulated on the progress made in such a short time.

From Montreal B.O.A.C. took us home to London, and the Fifth Anglo-American Aeronautical Conference was ended.

I can finish no better than by quoting the English Master

" I can no other answer make but thanks,
And thanks, and ever thanks."

(*Twelfth Night*)

A. M. Ballantyne

Secretary

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Honours Awarded to Members

Air Vice-Marshal W. A. Opie (*Associate Fellow*) was awarded the honour of C.B. in Her Majesty's Birthday Honours List.

Eleventh British Commonwealth and Empire Lecture

Dr. J. J. Green, M.B.E., F.R.Ae.S., F.I.A.S., F.C.A.I., will deliver the Eleventh British Commonwealth and Empire Lecture on Thursday 6th October at 6.0 p.m. on " The Growth of Aeronautical Research in Canada during the Post-War Decade " at the Royal Institution, 21 Albemarle Street, W.1. Tea at 5.30 p.m.

Associate Fellowship Examinations, December 1955

Although it was stated that the last examination in Part I of the old syllabus would be held in June 1955, it has now been decided to hold a final examination in this part in December in order to help a number of candidates who were unable to attend owing to the Railway Strike and various other reasons. Will those candidates who are interested please write to the Secretary giving full particulars of previous entries, if any.

Baden-Powell Memorial Prize

The Baden-Powell Memorial Prize, awarded to the best candidate in Part II of the Associate Fellowship Examination has been awarded to Mr. H. F. C. Newby.

Graduates' and Students' Section Reception and Annual Dance, 28th October 1955

The Graduates' and Students' Section have arranged a Reception and Annual Dance which will be held at the headquarters of the Society on Friday 28th October 1955 from 8.0 - 11.30 p.m. Tickets, price 7/6 single and 15/- double (including refreshments), are obtainable from members of the Committee or by post from Mr. E. J. Catchpole, 12 Amery Road, Harrow-on-the-Hill, Middx.

News of Members

Squadron Leader D. O. Buxton (*Associate Fellow*), formerly of the Combustion Department of the National Gas Turbine Establishment, has now taken up a post in the Aircraft Laboratory of the Wright Air Development Center.

Professor J. V. Connolly (*Fellow*), formerly Professor of Aircraft Production at the College of Aeronautics, Cranfield, is now Director of Sundridge Park Management Centre Limited.

G. W. H. Gardner (*Fellow*), at present Director-General of Technical Development (Air), Ministry of Supply, has been appointed to succeed Sir Arnold Hall as Director of the Royal Aircraft Establishment. He will take up the appointment on 1st November 1955.

Sir Arnold Hall (*Fellow*) has resigned his post of Director of the Royal Aircraft Establishment and has been appointed as Technical Director to the Board of the Hawker Siddeley Group. He will take up his new post on 1st November 1955.

W. G. Johnson (*Graduate*) has joined Rolls-Royce Ltd. (Scottish Group) as a Technical Assistant.

J. B. B. Johnston (*Graduate*) has been appointed a Senior Scientific Officer with the Ministry of Supply and has been posted to the Naval Aircraft Department at the National Aeronautical Establishment.

Captain A. G. Lamplugh (*Fellow*) has retired from his post of Underwriter and Principal Surveyor to the British Aviation Insurance Company and has joined the Board of the Company.

J. J. Pearson (*Graduate*), formerly with the London Office of the Bristol Aeroplane Company, has taken up a position as Aircraft Designer with A. V. Roe (Canada) Ltd., Ontario.

R. I. B. Tavener (*Associate Fellow*) is now Senior Technical Representative with Blackburn & General Aircraft Limited.

C. F. Toms (*Associate Fellow*) has been appointed Project Engineer (Civil Aircraft) to Hunting Percival Aircraft Limited.

W. W. Warner (*Associate Fellow*), formerly Factory Manager of the de Havilland Aircraft Company at Christchurch, has been appointed Chief Engineer of Airwork Limited at Blackbushe Airport.

Lt. Cmdr. G. O. Waters (*Associate*) has been seconded by British European Airways to the post of Chairman and Managing Director of Air Terminals Limited.

Diary

LONDON

24th **September**
GRADUATES' AND STUDENTS' SECTION.—Visit to R.A.F., West Malling. *See* separate Notice.

4th **October**
GRADUATES' AND STUDENTS' SECTION.—An informal talk on Aircraft Structural Fatigue. Dr. P. B. Walker, C.B.E. Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

6th October
MAIN LECTURE.—British Commonwealth and Empire Lecture. The Growth of Aeronautical Research in Canada during the Post-War Decade. Dr. J. J. Green, M.B.E. Royal Institution, 21 Albemarle St., London, W.1. 6 p.m. (Tea 5.30 p.m.).

12th October
GRADUATES' AND STUDENTS' SECTION.—Visit to National Aeronautical Establishment, Bedford. *See* Notice.

19th October
GRADUATES' AND STUDENTS' SECTION.—Rocket Films. Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

20th October
MAIN LECTURE.—The Jet Flap. I. M. Davidson. Royal Institution, 21 Albemarle Street, London, W.1. 6 p.m. (Tea 5.30 p.m.).

25th October
SECTION LECTURE.—Boundary Layer Effects in Supersonic Flow. R. J. Monaghan. Library, 4 Hamilton Place, London, W.1. 7 p.m.

28th October
GRADUATES' AND STUDENTS' SECTION.—Dance. Library, 4 Hamilton Place, London, W.1. 8.00 - 11.30 p.m.

BRANCHES

5th **September**
Halton.—The Problems of Interplanetary Flight. Dr. L. R. Shepherd. Branch Hut, R.A.F., Halton. 6.45 p.m.

12th September
Halton.—Films: Argon Arc Welding and others. Branch Hut, R.A.F., Halton. 6.45 p.m.

14th September
Halton.—Visit to Firth Brown Ltd., Sheffield.

19th September
Halton.—Films: Steelmaking and Toolmaking. Branch Hut, R.A.F., Halton. 6.45 p.m.

21st September
Coventry.—Report by E. D. Keen and Dr. W. F. Hilton on the Fifth Anglo-American Aeronautical Conference. The Wine Lodge, The Burges, Coventry. 7.30 p.m.
Southampton.—Aircraft Carrier Operations in the Korean Campaign. Lt. Cdr. Luby, R.N. Institute of Education, Southampton University. 7 p.m.

23rd September
Birmingham.—BRANCH AREA MEETING. Application of a Digital Computor to Gas Turbine Engineering. G. C. Best. Chamber of Commerce, New St., Birmingham. 7.30 p.m.

26th September
Halton.—Paper by an Aircraft Apprentice. Branch Hut, R.A.F., Halton. 6.45 p.m.

29th September
Isle of Wight.—Recent Development in Production Processes. W. E. Goff. Saunders-Roe Club House, Cowes, Isle of Wight. 7 p.m.

1st **October**
Halton.—Annual General Meeting. MAIN LECTURE: Compound Engines. A. C. Clinton. Branch Hut, R.A.F., Halton. 6.45 p.m.

3rd October
Halton.—Films: History of Helicopter Development. Branch Hut, R.A.F., Halton. 6.45 p.m.

17th October
Halton.—Film and Talk: Overseas Visits to Branches. Dr. A. M. Ballantyne. Branch Hut, R.A.F., Halton. 6.45 p.m.

19th October
Coventry.—Cockpit Hoods. Dr. A. Holland. The Wine Lodge, The Burges, Coventry. 7.30 p.m.

20th October
Southampton.—Gas Turbines: Basic Principles and Production Problems. C. E. Wurr. The Polygon Hotel, Southampton. 7.15 p.m.

31st October
Halton.—Problems of Space Flight. Flt.-Lt. R. W. Durrant. Branch Hut, R.A.F., Halton. 6.45 p.m.

2nd **November**
Southampton.—Flight Refuelling. P. S. McGregor. Institute of Education, Southampton University. 7 p.m.

BRANCH AREA MEETING—BIRMINGHAM BRANCH

An Area Meeting is being held at the Birmingham Branch on 23rd September 1955. Mr. G. C. Best, Head Performance Engineer, Orenda Engines Ltd., Canada, will lecture on the " Application of a Digital Computor to Gas Turbine Engineering." The meeting will be held at the Chamber of Commerce, New Street, Birmingham, at 7.15 p.m.

GRADUATES' AND STUDENTS' SECTION—VISITS

A visit has been arranged to the Royal Air Force, West Malling, for Saturday 24th September. This is an Operational Fighter Station, within easy reach of London, and applications for the visit should be made immediately to the Hon. Visits Secretary, Mr. P. D. Stewart, B.O.A.C. Operations Development Unit, London Airport, Hounslow, Middlesex.

A visit has also been arranged to the National Aeronautical Establishment at Bedford for Wednesday 12th October. It is hoped to arrange for a coach party to travel from London for this visit, and in order to complete these arrangements, early application should be made to the Hon. Visits Secretary as above.

ASSOCIATE FELLOWSHIP EXAMINATION RESULTS

The following candidates were successful in the Associate Fellowship Examination held in June 1955:—

PART I—LONDON

Flt. Cadet J. Armstrong, Aerodynamics I, Theory of Prime Movers and Fuels.

Sgt. A. Beedle, Applied Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I; Flt. Cadet T. J. Burns, Theory of Prime Movers and Fuels.

D. S. Carton, Aerodynamics I (*See also* Part II).

R. F. M. Drake, Aerodynamics I, Properties of Matter, Heat, Light and Sound, Theory of Prime Movers and Fuels.

Flt. Cadet P. R. Evans, Aerodynamics I, Theory of Prime Movers and Fuels (*See also* Part II).

Flt. Cadet M. Farmer, Aerodynamics I, Pure Mathematics, Theory of Prime Movers and Fuels.

E. T. Harris, Aerodynamics I, Pure Mathematics, Magnetism, Electricity and Electronics, Theory of Prime Movers and Fuels; K. G. Hodson, Theory of Prime Movers and Fuels.

J. R. Lyon, Aerodynamics I, Pure Mathematics, Properties of Matter, Heat, Light and Sound.

A. A. Munday, Aerodynamics I.
Flt. Cadet S. T. Newington, Pure Mathematics, Theory of Prime Movers and Fuels (*See also* Part II).
D. T. F. Ozanne, Aerodynamics I, Theory of Prime Movers and Fuels (*See also* Part II).
E. Roadnight, Aerodynamics I.
G. M. Turner, Magnetism, Electricity and Electronics.

PART II—LONDON

M. G. Cherry, Aerodynamics II.
Flt. Cadet P. R. Evans, Navigation (*See also* Part I).
T. E. Fitzsimmons, Strength of Aircraft Materials and Theory of Structures II.
D. Gill, Aerodynamics II.
M. J. Harris, Strength of Aircraft Materials and Theory of Structures II; S. M. Humphry, Strength of Aircraft Materials and Theory of Structures II.
K. R. Liversage, Aerodynamics II; M. H. Lock, Strength of Aircraft Materials and Theory of Structures II.
P. L. Manley, Aircraft Design; H. F. C. Newby, Strength of Aircraft Materials and Theory of Structures II (Baden-Powell Prize); Flt. Cadet S. T. Newington, Navigation (*See also* Part I); R. A. Nicol, Strength of Aircraft Materials and Theory of Structures II.
T. O'Brien, Aerodynamics II; T. Opatowski, Aerodynamics II; D. T. F. Ozanne, Navigation (*See also* Part I).
K. G. Page, Aerodynamics II.
K. M. Smith, Air Transport, Aircraft Materials.
D. H. Tipper, Strength of Aircraft Materials and Theory of Structures II; B. S. Ward, Aerodynamics II.

PART II—NEW SYLLABUS

L. A. Hall, Aerodynamics A, Aerodynamics B, Aerodynamics C.
N. W. Jones, Economics and Management, Production, Aircraft Manufacture.

PART II—OUTSIDE LONDON

G. T. O'Brien (Belfast), Aircraft Design.

PART I—ABROAD

K. G. Balija (Mysore, India), Strength of Aircraft Materials and Theory of Structures I.
R. Malet de Carteret (Calgary, Canada), Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I.
Tulsi Dass (Poona, India), Pure Mathematics, Strength of Aircraft Materials and Theory of Structures, Theory of Prime Movers and Fuels.
G. A. Hopkoper (Delft, Holland), Applied Mathematics, Aerodynamics I, Strength of Aircraft Materials and Theory of Structures I.
K. Kumar (Delhi, India), Aerodynamics I.
G. G. Mahajani (Madras, India), Pure Mathematics, Properties of Matter, Heat, Light and Sound, Aerodynamics I.
M. Shamarao (Mysore, India), Strength of Aircraft Materials and Theory of Structures; K. Sanjeevan (Mysore, India), Applied Mathematics, Magnetism, Electricity and Electronics, Aerodynamics I, Theory of Prime Movers and Fuels.

PART I—NEW SYLLABUS—ABROAD

V. Shirdher Hedge (Poona, India), Mechanics, Strength of Aircraft Materials and Theory of Structures I.

PART II—ABROAD

D. S. Carton (Karachi, Pakistan), Engine Design (1952).
Captain Milos Jelinek (Haifa, Israel), Air Transport, Navigation.
M. V. Karve (Bangalore, India), Strength of Materials and Theory of Structures II.
T. S. Nagesha Rao (Bangalore, India), Strength of Materials and Theory of Structures II; B. N. Vaman Rao (Bangalore, India), Engineering Economics.
M. Shamarao (Mysore, India), Strength of Materials and Theory of Structures II; Sucha Singh (Delhi, India), Engine Design; K. S. Subrahmanyam (Mysore, India), Aircraft Design.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellow

Peter Purdon Elliott (*from Graduate*)

Associates

Sydney Leedham
Arthur Frederick Mortimer
Robert Stanley Strath

Graduates

Peter Norman Dent
Michael John Heath
John Lovejoy Johnston (*from Student*)
Philip Roy Lancaster
Gerald Hoong Sun Lew-Sang
Robert William Murphy
Eric James Phillips (*from Student*)
Gordon Senior

Students

Frederick Nicholas Birkett
Walter Bruce Remington

JOURNAL BINDING

Permanent Binding

The new prices for permanent binding of Journals are:

1954 Volume (including packing and postage)	18s. 6d.
1953 Volume (including package and postage)	19s. 0d.
Previous Volumes (including packing and postage)	18s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters). New address (in block letters).
Grade of Membership. Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

REPRINTING ANNUAL REPORTS AND JOURNALS

The Council have agreed that the Annual Reports and the first fifteen Volumes of the *Journal of the Royal Aeronautical Society* be reprinted facsimile, as the stock of these publications is extremely low, and in some cases we have no copies at all. The Council would be very grateful to any member who could lend, or sell to the Society, copies of the issues which are missing so that this reprinting may be done. The missing numbers are:—

Annual Reports	*Journals*		
Nos. 1	Vol. I	1897	April
2	Vol. V	1901	April
4	Vol. V	1901	October
6	Vol. VII	1903	April
9	Vol. VII	1903	July
12	Vol. X	1906	January
18 and 19	Vol. XI	1907	April
20 and 21	Vol. XIII	1909	July
	Vol. XIV	1910	July
	Indexes to Vols. II, IX, XI and XIII		

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 59 SEPTEMBER 1955 NUMBER 537

The Structural Effects of Kinetic Heating in Supersonic Flight

by

P. B. WALKER, C.B.E., M.A., Ph.D., F.R.Ae.S.

(Royal Aircraft Establishment, Farnborough)

1. Introduction

The structural problems introduced by the kinetic heating of high speed aircraft require a radical extension of what has hitherto been regarded as the normal domain of structural theory. Aerodynamics, for example, cannot be regarded as a self-contained subject which merely provides basic data for the structural worker. Certain aspects of aerodynamic theory, particularly the mode of heat generation, have to be considered simultaneously with the structural problem. Thermodynamics and metallurgy are still more closely integrated with structural theory. The laws of heat transfer, and the variation of material properties with temperature, are both essential factors in the structural analysis.

In the initial approach to the structural problem the greatest difficulty arises from a tendency to undue complexity. There are a great many subsidiary problems which confuse the main issue and obscure the objective that lies ahead. The only solution to this difficulty is a ruthless simplification of the main problem in the first instance, followed by detail investigation as required later.

Such a simplification is attempted here, and the main objective of this paper is to reduce kinetic heating, from the structural standpoint, to fundamental principles. A simplified structure is first assumed with a simplified thermal system. The potentially adverse effects of kinetic heating upon the structure are then enumerated and methods of alleviation considered. In the initial approach the overall thermal condition is taken for granted as for a reasonably conventional design, but later, consideration is given to the possibility of modifying the thermal condition of the structure by means of insulation and artificial cooling. Although such control may not be strictly regarded as a structural problem, the structural specialist has the greatest incentive to protect the structure from excessive heating.

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Some consideration is also given in this paper to laboratory experiments, upon which ultimately depends a true understanding of structural behaviour. It is necessary to be able to reproduce in the structural laboratory the same thermal conditions as occur in high speed flight. Some of the work proceeding at R.A.E. is mentioned, and it is clear that, while the task of thermal simulation is extremely difficult, progress is being made.

Finally, the paper concludes with an estimate of the prospects of extending the frontiers of high speed flight so far as the structural limitations are concerned. There is already sufficient knowledge to predict a definite and significant advance without any revolutionary discoveries being made, but the scope for further advance would be greatly extended by the development of more suitable materials for either the structure itself or for its protective insulation.

2. Conditions of the Problem

For the study of principles the first simplification concerns the structure itself. For this we assume a thick-walled egg-shaped structure of the simplest possible form (Fig. 1). At a later stage it will be necessary to depart from this simple conception and introduce many complicated paths along which heat has to flow, but for the present the simple example suffices.

There is one particular property of this structure which can realistically be assumed. This is that it is made of material of high thermal conductivity. All the metallic materials used in aircraft construction satisfy this condition. There is no reason, of course, why non-metallic materials of low conductivity should not also be considered as a possibility, but for them some modification to the general conclusions would be necessary.

This simplified structure is then assumed to be completely surrounded by hot air, produced by high speed flight. It is not proposed to discuss in detail the aerodynamic principles under which this high temperature is produced. Without serious loss of generality it

may be assumed that the temperature of the external air in contact with the structure is uniform.

In general it may be taken for granted that the temperature inside the structure is low. This is true in all cases in the early, and usually the most critical stages of high speed flight. In many cases the low temperature will have to be maintained indefinitely, however, by artificial means, for the benefit of personnel and heat-sensitive equipment within the aircraft.

We thus have, in principle, two zones of air, one at high temperature, the other at low temperature. They are separated by a structural wall made of heat-conducting material. To the conditions thus imposed the structure is in some degree vulnerable, in ways that are to be considered next.

3. The Adverse Effects of Kinetic Heating from the Structural Standpoint

In principle there are four adverse structural effects of kinetic heating. These comprise:—

(*a*) Deterioration of structural material.
(*b*) Thermal Stress.
(*c*) Temperature Stress.
(*d*) Thermal Shock.

The words used in these headings have been carefully chosen, but unfortunately there is no standard terminology.

Deterioration of structural material (*a*) is, broadly speaking, the impairment of strength and stiffness properties as the direct result of high temperature. "Thermal Stress" (*b*) is stress produced by temperature gradients in the material. "Temperature Stress" (*c*) is the effect of temperature change upon materials in structural contact that have different coefficients of expansion. Finally "Thermal Shock" (*d*) is the effect of a sudden rise in external temperature.

3.1. DETERIORATION OF STRUCTURAL MATERIAL

Deterioration of basic material properties is probably the most serious of all the effects that are listed here. Both strength and stiffness properties of normal structural materials decline as appropriately high temperatures are reached. Of the two, loss of stiffness gives the greater cause for concern since not only may it give rise to catastrophic flutter but it may reduce compressive strength through premature buckling.

There are three lines of attack to the problem thus presented. The first is to make the best choice of structural material from those already in existence. Light alloy becomes suspect at about 150°C., but steel is effective at a much higher temperature. Titanium can be used at a higher temperature than is permissible for conventional light alloys but not so high as for steel. It is not difficult, however, to contemplate speeds at which all known materials are unsatisfactory if the structure is directly exposed to the air stream.

The second line of attack is to seek new materials with better high temperature performance. This is a somewhat idealistic approach, and whatever prospects of success the metallurgist may have, the structural specialist cannot wait for the results. In new fields of engineering it often happens that results follow a new demand. It is discouraging to note in this connection, however, that the demand for heat-resisting structural materials is long-standing for many engineering applications.

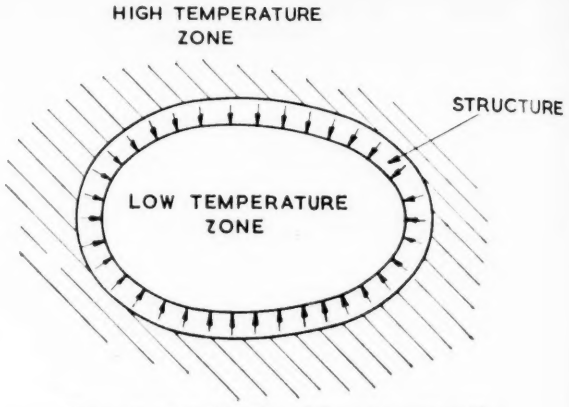


FIGURE 1. Simplification of the structural problem.

The third line of attack involves making the best choice of the available materials and attempting to overcome their disabilities by some ingenuity in structural design and by the acceptance of some weight penalty. To compensate for loss of material strength it may be permissible to increase the amount of structural material. Loss of stiffness may require in addition to increased material, a more effective stabilising system to prevent buckling and local flutter of panels. Creep is a particular form of stiffness reduction that might well be regarded as a separate problem. The time factor enters the picture here, and for short duration a certain amount of creep might be acceptable. For aircraft required to give long service, particularly long range transport aircraft, however, it seems unlikely that any appreciable degree of creep can be tolerated.

3.2. THERMAL STRESS

Differences of temperature within a structure give rise to a tendency to differential expansion. The structure may therefore be distorted to some degree, but usually there is a considerable resistance to distortion and it is this resistance which produces thermal stress.

If a structure is left to itself its temperature tends to become uniform and thermal stresses therefore tend to disappear. For this reason thermal stresses are sometimes referred to as "transient stresses". The term is not always appropriate, however, since where long flights are required cooling may be provided artificially (discussed later) and the steady state that is approached may be a persistent condition of thermal stress.

In principle, thermal stress might be avoided or reduced by choice of suitable materials. The main requirement for a material is that it should have a low coefficient of expansion. Unfortunately the prospects

of finding a suitable material with a low coefficient of expansion are not good, though there is clearly scope for metallurgical research. For normal temperatures materials with very low coefficients of expansion do exist, being widely used for accurate clocks and scientific apparatus, but their coefficients of expansion are at least as high as the general run of materials at the elevated temperatures under consideration. A reduction of thermal stress is also possible by use of materials with a low modulus of rigidity, but rigidity is a property that cannot be sacrificed on modern aircraft.

The scope for dealing with thermal stress by ingenuity in structural design is also very limited. In some cases alleviation of stress may be achieved by provision of extra material, not required for direct structural reasons, to give a more satisfactory path along which the the heat has to flow. Additional material to give increased strength is not fully effective, since thermal stress is related to strain; but relief of stress can be produced by increased material in respect of applied external loadings.

In general the existence of thermal stress may have to be accepted; but it is important to bear in mind that fatigue, as well as loss of static strength, has to be considered and may be the more serious hazard of the two. There is one complete loading cycle for each high speed flight and it may be necessary to impose a life limitation based on thermal stress. More research on fatigue at high temperatures is clearly needed.

3.3. TEMPERATURE STRESSES

It is necessary to make a clear distinction between what are here called "Temperature Stresses" and "Thermal Stresses", since the terms used are not necessarily distinctive in themselves.

Temperature stresses are an old problem in aircraft design and arise from the use, in the same structure, of materials having different coefficients of expansion. For supersonic aircraft, temperature stresses for given materials depend only upon the actual temperature of the structure, and although they are superimposed on the thermal stresses they are not directly related to temperature gradients.

The most direct way of avoiding temperature stresses is to avoid the use of dissimilar materials in a structure. Steel and aluminium-alloy, for example, are a bad combination from the standpoint of temperature stress since aluminium alloy has an appreciably higher coefficient of expansion than steel of a kind suitable for aircraft construction. It might be expected that unsuitable combinations of materials from the temperature stress standpoint could always be avoided. In practice, however, such combinations may be required in order to combat material deterioration without excessive weight penalty. Thus a basically aluminium-alloy structure might have a covering of steel or titanium sheet. In such cases the only practicable course is to weigh the penalties of temperature stresses against the advantages gained by the use of dissimilar materials.

3.4. THERMAL SHOCK

While thermal stresses are produced by temperature gradients within the structure, thermal shock is the result of a high time rate of increase of the external temperature. The classical text-books on thermal conduction make clear that the normal laws of conduction do not apply when the rate of rise of external temperature is extremely high. A sudden rise in external temperature, in fact, produces a disintegrating effect on the surface without any heat penetrating a measurable distance into the material. Destruction of the surface may therefore occur, and possibly be accompanied by progressive delamination.

The effect is not unknown in engineering. It may occur when steel sheets are suddenly placed in a hot furnace. It may also occur in aero-engines when internal surfaces are suddenly exposed to flame.

Fortunately thermal shock is not to be expected on supersonic aircraft at speeds likely to be attained in the near future. The main reasons for this are the time taken for the aircraft to accelerate and, from the standpoint of thermal shock, the still comparatively low temperatures that are attained. Thus, while thermal shock should not be disregarded in a study of principles, it is well outside the thermal frontier at the present stage of development.

4. Artificial Cooling

The effects produced by kinetic heating may be influenced by artificial cooling within the structure. Such cooling might be introduced deliberately as a means of protecting the structure, an aspect discussed later under the heading of "Insulation". At this stage it is proposed to consider artificial cooling only as something introduced primarily for reasons that have nothing to do with the structure, but which need to be considered from the structural angle. For high speed flight it is necessary to cool the inside of the aircraft for the benefit of the personnel on board. Cooling may also be necessary to protect heat-sensitive controls and equipment.

The effects of cooling the inside of the structure may conveniently be considered in terms of the diagrams in Fig. 2. In these diagrams the line AB represents a line of heat flow, the source of heat being indicated by the plus sign. Temperatures are shown at arbitrary time intervals as curves in the diagrams, and temperature gradients are to be deduced from the slopes of these curves.

Conditions without cooling are considered first (Fig. 2*a*). In this case heat is absorbed by the structure itself so that there is a general rise in temperature along the line AB. Two fundamental facts emerge from this case. The first is that the highest temperature gradients, and hence the highest thermal stresses, occur in the initial stages. The second is that the condition of thermal stress steadily disappears as the structure approaches a condition of uniformly high temperature.

In the next diagram (Fig. 2*b*) the effect of cooling is illustrated, with the source of cold or sink of heat

denoted by the minus sign. The first principle this diagram illustrates is that cooling scarcely affects the initial high temperature gradients and thermal stresses. The second principle is that cooling stabilises a condition of temperature gradients that, although generally less serious than the early transient cases, persist for the duration of high speed flight.

From the standpoint of thermal stresses, therefore, cooling cannot, in general, be regarded as beneficial. From the standpoint of material properties, however, it may be considered an advantage to have the inner portions of the structure at a relatively low temperature. It might then be possible, for example, to confine the special heat-resisting materials to the outer parts of the structure only; thus a structure basically in aluminium alloy might be covered with steel or titanium sheeting. In such cases, however, regard would have to be paid to temperature stresses produced by dissimilar materials in addition to thermal stresses.

5. External Insulation

When thermal insulation is brought into the picture an entirely new approach to the structural problem of kinetic heating is inaugurated. So far concern has been with the structural and metallurgical treatment of stipulated thermal conditions. We now have to consider the prospect of alleviating the structural difficulties by controlling in some degree the thermal condition.

In principle, owing to the high conductivity of the metal structure, the effect of a thin outer layer of insulation is remarkable. The effect is illustrated diagrammatically in Fig. 3. Insulation without cooling is considered first (Fig. 3*a*). Initially the main fall of temperature takes place across the insulation, and both the temperature of the structure and the temperature gradient are low. As time goes on the temperature of the structure rises and would ultimately reach the same uniform temperature as would occur without insulation, although the rise will be delayed. At all stages, however, the temperature gradients and thermal stresses remain low.

To obtain full benefit of insulation cooling is necessary and we pass to Fig. 3*b*. The general rise of temperature is prevented and we thus virtually eliminate both the hazard of material deterioration and the hazard of high thermal stresses.

The effect of the presence of insulation upon the cooling is also significant. Without insulation the amount of refrigeration required at fairly high subsonic speeds may be excessive, and beyond practical resources. To cool the cabin without external insulation, in fact, it might be necessary to insulate the inside of the structure to make cooling practicable. External insulation enables the same cooling to be applied to serve two purposes, *i.e.* to protect both the structure and the contents of the aircraft.

The development of a suitable external insulator is a major problem, but the indications are that it is not an insuperable one. With the structural materials at present available, moreover, insulation may prove the only solution for achieving flight at very high speeds.

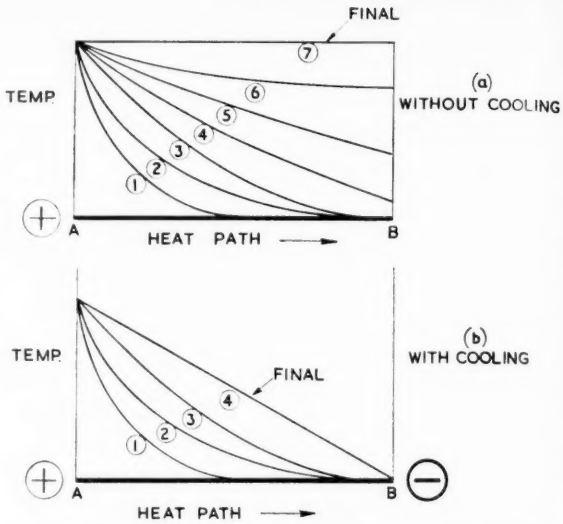


FIGURE 2. Temperature gradients without and with cooling (no insulation).

Cooling also has its difficulties but they are perhaps less serious. Refrigeration is the most direct method but at high speeds this may be impracticable. Any air brought into the aircraft will be hot owing to kinetic heating. In principle, the second law of thermodynamics still allows refrigeration provided that air is ejected at a temperature still higher than that of entry, but the possibility of leakage of heat cannot be overlooked and the instinctive objection to cooling by hot air has some justification.

The alternative is to carry "cold fuel", that is material at low temperature that is carried as a sink of heat. It appears practical for the "cold fuel" to be literally fuel in the normal sense, the fuel being taken on board at a low temperature and used first for cooling and then for propulsion.

6. Laboratory Research

In the fight to overcome the effects of kinetic heating, laboratory research has an important place. To assess the adverse effects of kinetic heating it is essential to be able to simulate in the structures laboratory the external heating conditions and to measure the structural response. This is a task that is much more difficult than might be supposed, and much depends upon a successful outcome.

There are two main problems to be solved. The first is how to produce the necessary rate of heat supply to the external surface of the structure under investigation. It is only when actual calculations are made that it is realised how effective a supersonic aircraft can be as a primary heat generator. For a Mach number of 4·0 at 50,000 ft. for instance, a thermal density equivalent to about 20 kilowatts per square foot of surface is reached.

The second main problem is to produce a heating system that has a quick response to control. It is not sufficient merely to be able to regulate the heat flow and temperature without regard to the time taken. A quick response to control is necessary in order to be able to reproduce the complex time-temperature pattern that is produced aerodynamically as the aircraft accelerates to its high supersonic speed.

Several methods have been tried or investigated, and dismissed as impractical for one reason or another. Among such methods are the placing of the structure in a hot furnace, the use of specially designed electric pads or blankets, and the use of electric fire-bars similar to those on an electric fire.

The first promising method is the use of infra-red lamps, upon which much work has been done at R.A.E. Infra-red lamps have the advantage of a low "thermal inertia", *i.e.* a ready response to control; but the ordinary commercial types do not produce enough heat. By encouraging the makers to develop lamps especially for this work, and by deliberately overloading and accepting the consequential reduced working life, the stage has been reached where it is considered that an absorption of 20 kilowatts per square foot, corresponding to flight at Mach number 4·0, is attainable. Fig. 4 shows a quartz cylindrical infra-red unit which meets these requirements. It is 14 in. long and $\frac{3}{8}$ in. diameter. The normal capacity is one kilowatt, but three kilowatts are obtainable by overloading.

Another method, which has not yet, at the R.A.E. at any rate, reached the same stage of development, is by

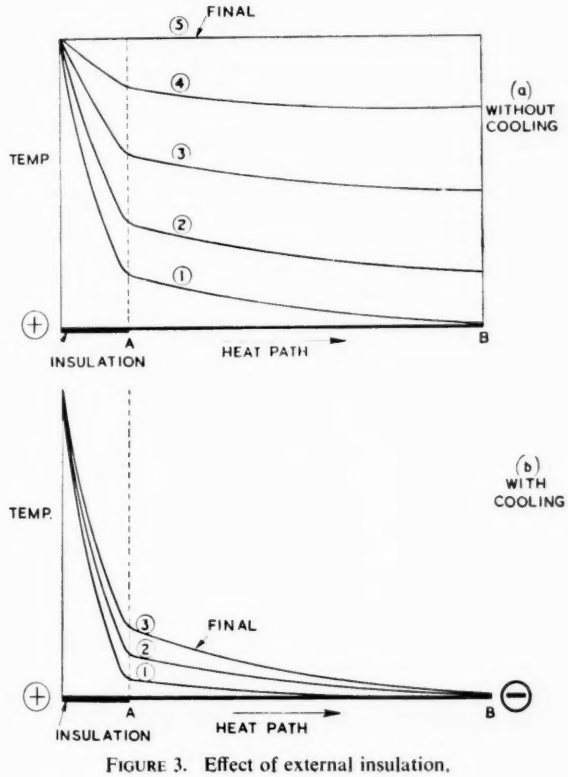


FIGURE 3. Effect of external insulation.

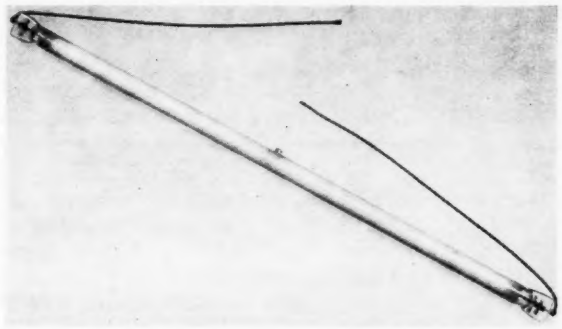


FIGURE 4. Quartz infra-red element (incandescent type).

electromagnetic induction. By operating at high frequency (say one megacycle per second) it is possible to restrict the primary heating to the outer thousandth of an inch of surface, so that for practical purposes virtually all the heat transfer inwards is by conduction. The main advantage of induction heating is the high rate of heat generation, which can greatly exceed that of the infra-red lamp. Control, however, is more difficult and may never be so good as for infra-red lamps.

To simulate the time variation of heat production an electronic simulator has been developed at R.A.E. Into this simulator data supplied by aerodynamicists is fed, and the desired time-temperature pattern reproduced. So far the simulator has been mainly used with infra-red lamps, and its use with induction heaters is still a matter for investigation.

With the means of producing the thermal conditions at hand, the next problem is to measure its effects upon the structure. The most important parameter is temperature, and two successful methods of temperature measurement have been evolved. One works on the thermo-couple principle and the other uses the change of resistance of a wire stuck to a surface.

The next most important parameter is strain. For this, strain gauges that are a development of standard electrical-resistor strain gauges have been produced by various workers. Although some claim greater success than others, it is doubtful whether strain gauges can as yet be relied upon and, in any case, they appear to be unsuitable for use at really high temperatures. There are, of course, many other possible alternative methods for measuring strain.

7. Conclusion—Extending the Thermal Frontier of Speed

When consideration is given to extending the thermal frontier of speed, it is natural to ask where the frontier is now. To this no definite answer can be given, and it is proposed to begin with aircraft just entering the supersonic range. From this position it is possible to make a somewhat idealistic plan for the advance to be made in three fairly distinct stages so far as the structural problems are concerned.

The initial advance from Mach number 1·0 is possible with structurally conventional aircraft made of

conventional light alloys. It is well-known that many aircraft have passed the so-called sonic barrier without structural difficulties from kinetic heating. How far it is possible to advance in this way is largely a matter of opinion, but a Mach number of 2·0, and possibly a little more, should be attainable at high altitudes.

The next stage of advance calls for special study of kinetic heating but no really revolutionary changes. In general, light alloy will have to be superseded by steel. The best aluminium alloy begins to deteriorate at 150°C., and must not be used, at least in the hotter parts of the structure. Titanium is an alternative to steel in the earlier phases of the advance, if its cost is considered justified; but at the higher speeds in the range contemplated this also fails, while steel is still satisfactory or at least acceptable. It is difficult to set precise limits to this second stage of the advance, but a Mach number of about 5·0 is suggested.

The third stage requires more revolutionary changes and is to some extent hypothetical. The structure will need to be protected from the external temperature by insulation, and in many cases heat will have to be removed by refrigeration or absorbed in cold material carried for the purpose. This pre-supposes the development of a suitable insulating material and a technique for efficient cooling. Neither of these, it is suggested, should be regarded as an unduly optimistic aim.

The whole plan of advance, as here envisaged in its three stages, however, may have to be re-cast if new structural material is discovered with better heat-resistance properties from the standpoint of both material deterioration and coefficient of expansion. The incentive for metallurgical research is high, but it would be unrealistic to base plans upon the hypothesis that a revolutionary discovery will remove the obstacles that now stand in the way.

Some Trends in the Development of Aircraft Electrical and Starting Systems

by

R. H. WOODALL, M.I.E.E. F.R.Ae.S.

(Technical Director, Rotax Ltd.)

1. Introduction

The main task of the aircraft accessory designer is to provide fully developed and type-tested equipment to meet the needs of the Aircraft Industry at the time when a new aircraft is at a stage in construction where accessories are to be fitted.

But he must do more than this, particularly with equipment for multi-engined aircraft. He must endeavour to set up and test a complete aircraft ancillary power system. This is particularly important for the electrical system, where two or more generators have to operate in parallel, successfully sharing the load on the system and providing over-voltage and other protection in such a manner that failure of the complete system does not result from failure of one engine, generator or its attendant equipment.

Since the accessory engineer's knowledge of the constructor's requirements may be not much more than 12-18 months from the proposed date of flight of the first prototype, it will be realised that systems, and components which comprise these systems, capable of meeting the operational requirements of the aircraft, must be in an advanced state of development at the time when the actual loads and so on are formulated.

The accessory manufacturer therefore should be designing equipment at any time for aircraft which will not fly for two years of more. Such a favourable state of affairs is not always reached, since the operational requirements of future aircraft are not always known at a sufficiently early date. Greater efforts will have to be made by manufacturers of equipment and of basic materials if the desirable ultimate goal is to be achieved.

In addition, more components and systems testing under simulated flight conditions will be required.

This paper deals mainly with electrical accessories and systems, but also outlines trends in non-electrical starting systems. Present-day ancillary electrical power systems will be briefly outlined and their limitations will be shown.

The trend in aircraft design is towards higher altitudes and higher speeds and it will be shown that these two factors involve many problems in both systems and equipment design.

With altitude increases, more difficult cooling problems are involved, since above 40,000 ft. reductions in density are not accompanied by corresponding reductions in air temperature. This means that if air is used as the heat sink for losses in the equipment, greater drag penalties are imposed on the aeroplane.

More serious is the effect of higher speeds, since stagnation air temperatures rise with speed, due to adiabatic compression of the air as the aircraft flies through it. The rise in air temperature is proportional to the square of the aircraft speed in miles per hour and is approximately equal to $(V/100)^2$.

Steps which will have to be taken to combat these problems will be dealt with later. Proposals will be made for the shape of future electrical systems which will tend to increase reliability and reduce weight.

Likewise, starting systems development is being directed towards reduced weight and to self-contained systems, particularly on fighter aircraft where the necessity for a quick start is now being emphasised.

2. Present-Day Systems

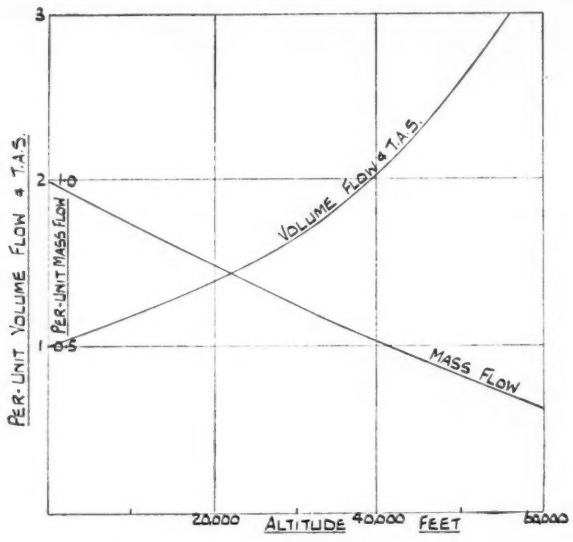
At the present time, British military and civil aircraft carry electrical generating equipment according to their size, from a few hundred watts to 292 k.v.a. capacity. In 1949 the author[1] showed a rough relationship between total generator capacity and aircraft all-up weight for civil aircraft of that period. Since that time, the generator capacity for a given aircraft gross weight has been nearly doubled on certain civil aircraft.

In Great Britain, system voltages have been standardised at 28 volts and 112 volts d.c. and, in addition, variable frequency a.c. is used at a voltage of 208. Apart from single-engined types, which up to the present use 28 volts d.c. only, most aircraft make use of two of these supplies. Quite a number, in fact, use three primary supplies.

There are several methods employed for generating these supplies. In some cases, separate d.c. generators and alternators are used, but in many instances alternators are used as main generating plant and rectifiers are fitted to obtain the low and medium voltage d.c. supplies as required. In all cases, generators have to operate over the entire speed range and a.c. generators directly driven by the engine accordingly give a supply at varying frequency.

On certain large military bombers no variable frequency a.c. is used. 112 volt d.c. generators are fitted to these aircraft and the 28 volt supply is derived from

Section Lecture given to the Society on 8th February 1955.



$$\frac{V_A}{V_O} = \frac{1}{\sqrt{\sigma}} \text{ and } \frac{m_A}{m_O} = \sqrt{\sigma}$$

Where: V_A = Volumetric flow at altitude
V_O = Volumetric flow at sea level
m_A = Mass flow at altitude
m_O = Mass flow at sea level
σ = Relative density

Based on I.C.A.N. tables.

FIGURE 1. Air flow *versus* altitude at constant I.A.S.

the 112 volt source by means of step-down rotary transformers.

Secondary supplies at 115 volts 400 cycle are available on most aircraft, the source being an inverter operating from the 28 or 112 volt system. The output may be either single or three phase. These inverters are both voltage- and frequency-controlled and provide a supply for navigational instruments and certain radio and radar equipment.

Some aircraft require an a.c. supply at 1,600 cycles, and here again an inverter is employed.

2.1. LIMITING FEATURES

Present day systems were designed to meet the operational conditions as required for the particular aircraft.

2.1.1. *Ram-air cooled machines*

2.1.1.1. *Altitude limitation*

Generators and other apparatus which require ram air for their effective cooling are limited in their altitude performance as already explained, by virtue of the relationship that exists between their sea-level and altitude temperature rise.

Figure 1 shows the relationship between mass-flow and altitude, assuming constant I.A.S. (indicated air speed); both T.A.S. (true air speed) and volumetric flow increase with altitude and the mass-flow is proportional to $\sqrt{\sigma}$, where σ is the relative density.

The curves for permissible G.L. temperature rise in flight, as shown in Fig. 2, were based on these assumptions, the temperature rise at any altitude being inversely proportional to mass-flow.

When present-day generators were designed, the maximum continuous safe temperature for the hottest part of the windings of rotating machines was considered to be 150°C. and it will be seen from the curve that at 55,000 ft., this corresponds to a sea-level temperature rise of 63°C. In fact, maximum temperatures in current machines can be allowed to reach 180°C. with safety, since in most instances the machine would not be fully loaded, except in failure of two engines of a four-engined aircraft, while in the single-engined aircraft shorter generator life could be permitted, the effect of the higher temperature from the insulation angle tending to reduce the life of the component. As far as temperature only is concerned, such generators would be suitable for operation at 60,000 ft. at a specified flight speed.

It will be noticed that on this curve the ambient air temperature at 60,000 ft. is shown as −30°C., which was the specified figure at the time when current machines were designed. This means, as will now be shown, that current generators are suitable for aircraft speeds of Mach numbers 0·5 to 0·8 at 60,000 ft. altitude, the lower figure corresponding to temperate summer conditions and the latter to I.C.A.N.

Alternatively, such generators would be suitable for 0·7 to 0·9 Mach number at 50,000 ft.

2.1.1.2. *Speed of aircraft limitation*

The stagnation air temperature, which is equivalent to the temperature of ram air available for cooling purposes, rises with increasing aircraft speed and the rise is proportional to the square of the speed in miles per hour.

This is shown on Fig. 3 for sea-level and 36,000 ft. or over, the shaded area showing the temperature attained under I.C.A.N. and temperate summer conditions.

Under flight conditions, of a Mach number of 1·5,

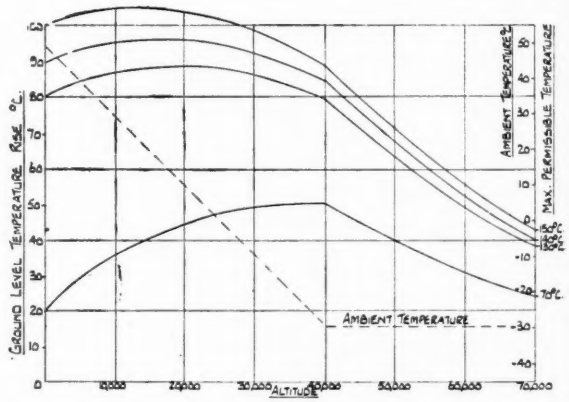


FIGURE 2. Curve showing ground level temperature rise to ensure maximum generator temperature at 130°C. to 150°C. for any altitude.

ram-air temperature at 50,000 ft. can reach 60°C., while at a Mach number of 2, the figure can be as high as 134°C. at the same altitude.

It will thus be seen that satisfactory operation of generators and other equipment at these speeds can only be achieved by one or more of the following means:—

(*a*) Increase in efficiency of the component.

(*b*) Increase in its operating temperature.

(*c*) Change in the heat sink and method of cooling.

It should be stressed, however, that regarding (*b*), the curve shown on Fig. 1 and subsequent calculations are based on the assumption that the machine efficiency remains constant for all altitudes. While this may be a fair approximation for maximum winding temperature of 150°C. or so, insomuch that increases in copper losses are more or less balanced by decreases in windage losses, there will be a falling off in efficiency due to extra copper losses when winding temperatures attain figures as high as 250° to 300°C.

While with a generator this may not seriously affect the performance at minimum speed, it will certainly have a further effect on the cooling problem. With inverters, however, the effect on the output can be important, and unless increases in efficiency or reductions in weight can be brought about by improvements in the iron circuit, and so on, it appears that some increase in size of such machines may be inevitable.

2.1.1.3. *Brushwear limitation*

The wear of brushes of generators and inverters which are subjected to the dry air conditions associated with high altitude flight has presented a problem to the electrical equipment designer for many years. Much work has been done in an endeavour to eliminate this wear and much has been written[2]. It is therefore not proposed to deal with the theory of film-forming adjuvants or with the various types which have been tried.

Suffice it to say that this excessive wear of brushes puts a severe limitation on d.c. machines generally and, to a certain extent, is apparent with the slip-ring brushes of rotating field alternators. Since much lower current densities can conveniently be employed with slip-ring brushes than with the main brushes of d.c. machines, the problem is somewhat eased.

Again, although impregnated brushes of recent type appear to show a considerable reduction in wear, they have very poor commutating properties and even with carefully designed d.c. machines, a short life is obtained, unless substantial de-rating is possible.

It does appear that a new approach to high altitude brushes is needed. The cored type of brush in which the adjuvent is inserted in holes through the brush surface may prove more promising.

2.1.1.4. *Weight and efficiency*

Generator design is a compromise between weight and efficiency considerations and it can be shown that for overall weight, including fuel, there is an optimum generator weight, and such a generator would not give

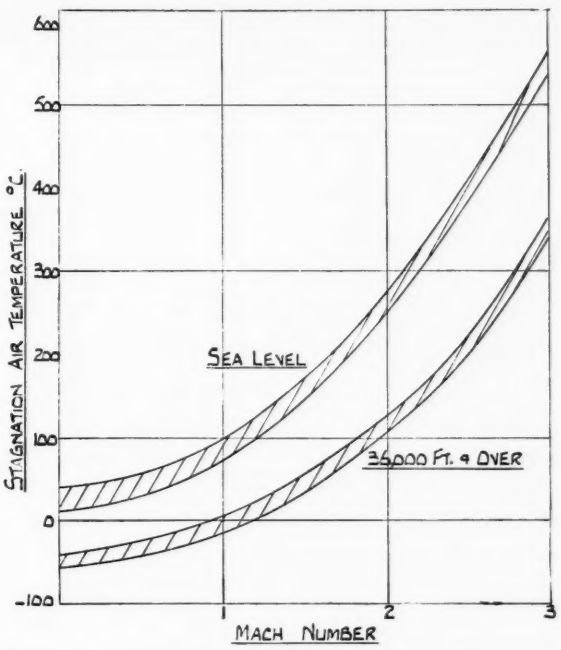


FIGURE 3. Stagnation air temperature due to adiabatic rise.

the maximum efficiency possible with larger and heavier designs.

Present-day machines were designed, in most instances, to meet space limitations imposed by engine mounting conditions and to ensure that the top temperature limitations of the insulating and other materials were not exceeded when mass air flows at altitude were maintained at specified figures. The altitude requirements were stated to be 50,000 ft. and aircraft speeds of 525 m.p.h. or so were assumed. At this speed, under I.C.A.N. conditions, the rise due to kinetic heating is about 27°C. only.

For continuous operation, the insulation materials available had a top temperature limit of about 150°—170°C. This would result from a machine temperature rise of about 185°C. at 50,000 ft. at 500 m.p.h., the ram-air temperature under these conditions being −15°C.

It so happens that present-day generators are, in fact, operating at an efficiency closely approximating to that of minimum carried weight.

The importance of reducing the sea-level temperature rise of electrical machines is evident. This can only be brought about by improving the efficiency, or by changes in the internal design to reduce the mass flow of air required to cool the machine. As already stated, increases in efficiency tend to increase generator weight and size and the penalties are severe, but some improvement can be effected by careful choice of materials and some aspects of this will be outlined later.

2.1.1.5. *Bearings and their lubrication*

Increase in generator maximum temperature leads to increase in bearing temperature, and we are already

very close to the maximum bearing temperature at which grease lubrication is possible. Use of grease retaining seals built into ball bearings can perhaps increase the maximum temperature to which such bearings can operate but, nevertheless, consideration must be given to alternative methods of lubrication and to the design of bearings of materials suitable for the high temperatures to be experienced under supersonic flight conditions.

2.1.1.6. *Oil seals*

Again there are serious limitations with present-day synthetic oil seals, both from the temperature and component speed angle, and also in their ability to operate satisfactorily with the new ester-based lubricants. A new approach to this problem is needed, since, in addition to temperature increases predicted, it will be desirable, in some instances, to increase generator speeds in order to reduce weight.

2.1.2. *Intermittently rated machines*

These machines rely for their cooling on natural convection, plus radiation and some conduction to mounting brackets and so on, but in many instances the steady state temperature is unlikely to be reached during normal operation.

Higher ambient temperature of the air surrounding the machine will cause higher maximum temperatures and there is therefore a temperature limitation with such machines, particularly with engine-mounted components and equipment in close proximity to the engine; with increases in engine bay temperatures, the necessity for starter motors, actuators, ignition units, and so on to withstand 250°C. soak temperature becomes apparent.

These higher temperatures are, in the first instance, associated with the de-icing of the air intake, but with supersonic flight, this temperature, and even higher figures, will have to be met.

2.1.3. *Static equipment*

There is a temperature limitation associated with all static electrical equipment on present-day aircraft.

Relays, contactors and all types of switchgear and protective devices utilise a coil employing insulated wire and impregnated with varnish. Solid dielectric material is also used for formers and bases.

All these have a top temperature limitation. In addition, there is a minimum operation voltage depending upon temperature, and if thermal trip devices are used, the range of ambient temperature for reasonable trip times also becomes a limitation.

Present-day switchgear, particularly that associated with 112 volt d.c. circuits, is limited in its rupturing capacity at high altitudes.

Perhaps the biggest penalty associated with static aircraft components is in the use of rectifiers and condensers, and these play an important part, not only in radio and radar equipment, but in any rectified a.c. system and in control units for inverters and for jet engine temperature and speed.

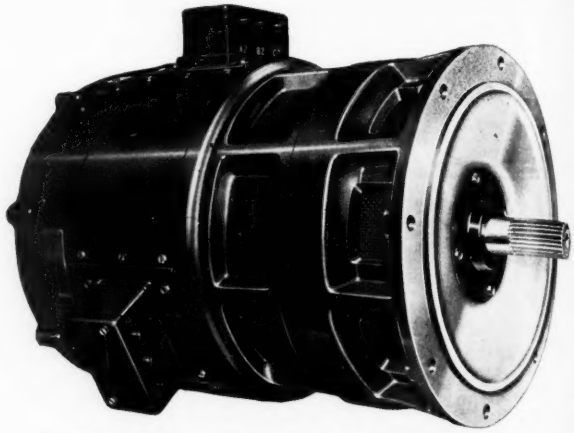


FIGURE 4. A Rotax 73 k.v.a. alternator, 4,700-9,800 r.p.m.

Present-day rectifiers of the selenium type have a maximum permissible temperature of 100°C. and therefore present a serious cooling problem. Batteries of the conventional lead-acid type have a serious drawback in their tendency to run away with increase of ambient temperature and slight increase in charging voltage.

2.1.4. *System reliability and weight*

Worthwhile weight reduction and further improvements in the reliability of current electrical systems are difficult, for the following reasons:

(*a*) All generators have to give full output over the entire engine speed range of 3·5 to one. This means that the size of the unit is fixed by the minimum speed. This cannot be increased with d.c. machines, since there is also a maximum speed limitation due to commutator and brushgear. Although some increase in maximum speed is possible with alternators, bearings will present a problem if speeds in excess of 12,000 r.p.m. are employed.

Commutator machines are very difficult to design to give good commutation over a wide speed range and, with the use of present types of high altitude brushes, the problem is accentuated.

(*b*) With d.c. machines, voltage regulator must involve moving armatures, with carbon discs or some form of vibrating contact with a fixed resistor. With a.c. varying frequency, the position is much the same.

(*c*) With d.c. systems, all motors used for ancillaries must have commutators and brushgear. With a.c. of varying frequency, rectifiers must be provided and, again, in most cases, d.c. motors must be used.

An attempt to use a.c. induction motors over a wide frequency range leads to excessive motor weight if system voltage is maintained.

(*d*) Inverters, which are inherently heavy and have low efficiency, must be used for a.c. supplies of controlled voltage and frequency with all current electrical systems, whether they be d.c. or rectified a.c. Similarly, any change in voltage of d.c. systems can only be effected by means of rotary machines.

3. Future Trends

Design and development work is now being directed towards the evolving of systems and equipment which will meet the aircraft operational requirements of the future.

Consideration is being given to equipment which will satisfy conditions at a Mach number of 2 and will be satisfactory at altitudes up to 60,000 ft. In addition, considerable thought is being given to the electrical system as a whole to improve its reliability and to reduce its weight.

3.1. SYSTEMS

Total generator capacity is likely to increase during the next decade and it is predicted, in some quarters, that large military bombers and transport aircraft will carry generating equipment up to 600 to 700 k.v.a. and that even fighter aircraft power requirements may exceed 200 k.v.a.

Even if these forecasts are unrealistic, and they may be since they visualise, for bombers, over 400 k.v.a. for de-icing purposes, it does appear that 400 or 500 k.v.a. is a likely requirement for large bombers and transport aircraft, and that fighters could carry up to 60 to 70 k.v.a. in the not too distant future.

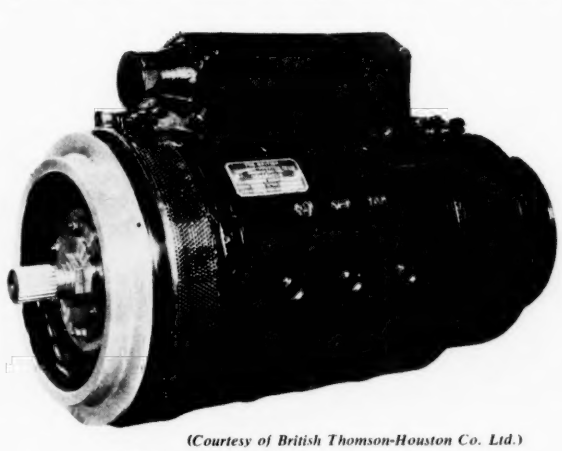
The largest available alternator in Great Britain has an output of 7.3 k.v.a. (Fig. 4) and it appears that some larger machines, probably up to 100 to 120 k.v.a., may be required.

D.C. generators up to 400 amps. at 28 volts will be available and perhaps represent the largest low-voltage direct current machines which should be attempted. A typical wide speed range generator is illustrated in Fig. 5.

3.1.1. *A.C. constant frequency systems*

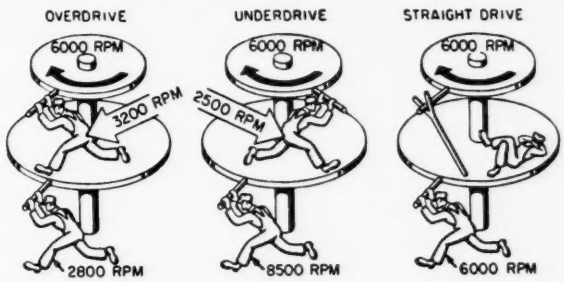
While it is not easy to generalise on the shape of future systems, the trend for the large aircraft, whether it be a military or a civil transport type, should be towards the use of constant frequency alternating current.

Such a system, when fully developed, will give the lightest and most reliable arrangement. It can at once effectively deal with the brushwear problem, ease cooling problems and make it more possible for switchgear to break the highest currents experienced when faults occur.



(Courtesy of British Thomson-Houston Co. Ltd.)

FIGURE 5. 40 k.w. d.c. generator.



(Courtesy of English Electric Co. Ltd.)

FIGURE 6. Principle of hydro-mechanical drive.

The necessity for inverters will be obviated and increased reliability will result from the use of a.c. squirrel-cage motors. Heavy radio interference filters will no longer be required.

These, and other advantages arising from the use of a constant frequency alternating current system have been outlined on many occasions during the past fifteen years, both in this country and in the U.S.A.[3].

The two obstacles which have prevented its earlier adoption in this country have been associated with the method of producing the constant frequency supply and the need for emergency electrical power in the event of main engine or fuel supply failures.

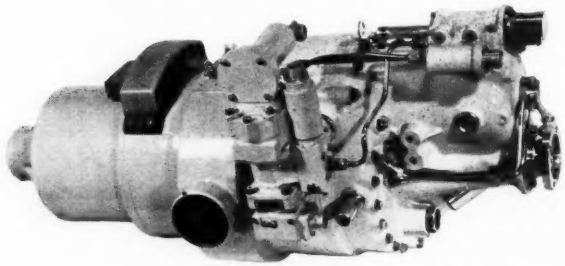
3.1.2. *Drives for alternators*

During the past fifteen years, seven methods of driving alternators at constant speed have been considered and these are shown in an order arising from their state of development at the present time, but not necessarily indicating what further development of these types may reveal to assist in assessing the relative merits of all these methods in the future.

(*a*) Hydro-mechanical constant speed drive, driven by main engine.
(*b*) Air turbine motor taking bleed air from compressor of main engine.
(*c*) Gas turbine motor, taking bleed air from compressor of main engine, and which is mixed with fuel and burned.
(*d*) Hydraulic drive, *i.e.*, hydraulic pump driven by engine and hydraulic motor driving generator.
(*e*) Mechanical drive—Hayes type.
(*f*) Mechanical drive—Beier gear.
(*g*) Auxiliary gas turbine engine.

3.1.2.1. *Hydro-mechanical drive*

Considerable effort has been expended in the U.S.A. in the development of a range of drives of this type, notably Sundstrand, and their fitment on one particular Service aircraft has made it possible for a considerable amount of experience to be gained. It is now claimed that such units have a trouble-free life of 700 to 800 hours.



(*Courtesy of English Electric Co. Ltd.*)

FIGURE 7. Sunstrand hydro-mechanical drive, 40 k.v.a., 3,000-8,000 r.p.m.

The basic principle of this drive is illustrated in Fig. 6. Originally designed for use with piston-engines where a narrow input speed was required, they are now available in several forms for use on gas turbines.

Their inherent disadvantages are associated with installations in which they have to be mounted in close proximity to the engine and this area is usually congested. If by their use the frontal area is increased, increased drag will result. In addition, drag penalties also result from the necessity to cool the oil, the losses being high under maximum engine speed conditions. Fig. 7 shows a typical drive unit rated at 50 h.p. continuous.

Current U.S.A. hydro-mechanical drives cover an input speed ratio of 2·7 to 1 only. In Great Britain, full power is stated to be necessary over a 3·5 to 1 engine speed range. Currently quoted weights for these drives are shown in Fig. 8, and there might be a considerable increase in these figures if the required speed range is to be met. The ratio of 2·7:1, which represents an input speed range of 3,000 to 8,000 r.p.m., would barely cover the requirements of some of our recent aircraft.

3.1.2.2. *Air turbine drive*

This is a more recent development and arises from the introduction of the gas turbine engine in which the use of bleed air taken from one of the compressor stages looks attractive.

Five or six years ago development of a range of such air turbine motors was initiated in the U.S.A. and while there is, as yet, little service experience with this drive, it undoubtedly shows promise.

On the face of it, it should be possible, as far as basic weight is concerned, to compete very successfully with the hydro-mechanical drive referred to, since it eliminates some of the complexity of these units. In essence, a small turbine wheel drives the accessory directly or through gearing, a typical unit driving a 15 k.v.a. alternator being shown in Fig. 9.

The attraction of using bleed air for air conditioning, de-icing and accessory cooling, has led to a situation where further bleed air demands for air turbine drives may, under certain flight altitudes and speeds, lead to penalties either in weight of increased fuel or in reduced range.

Basic weights of some units are shown on Fig. 8, and it will be seen that these are rather lighter than corresponding hydro-mechanical drives.

With air turbine drives, it is possible to install the turbo-alternator units in a more central position and avoid the weight of heavy cables necessary for transmitting the full generator output from the engine to the main busbars.

On the other hand, ducting for fairly hot air has to be substituted, but with ducting already installed for other bleed air requirements, the additional penalty would not be high. In addition, engine failure does not lead to failure of the electrical generating system, since common ducting will exist between the compressors of all engines.

The maximum power available from an air turbine drive is directly related to engine thrust and is also dependent upon turbine efficiency.

The horse-power which can be extracted from every pound of compressor bleed air, termed the adiabatic head, will vary with bleed air temperature and pressure, and while at all altitudes and cruising speed there is adequate adiabatic head, there is a marked falling off in the head from altitude to sea level with the engine idling.

The efficiency of an air turbine running at different speeds is shown on Fig. 10. This shows the sharp fall off in efficiency which occurs at low pressure ratio and it is unfortunate that, at these lower engine speeds and lower altitudes, the adiabatic head is low.

Obviously, one wants to have the point of maximum turbine efficiency at the pressure ratio associated with

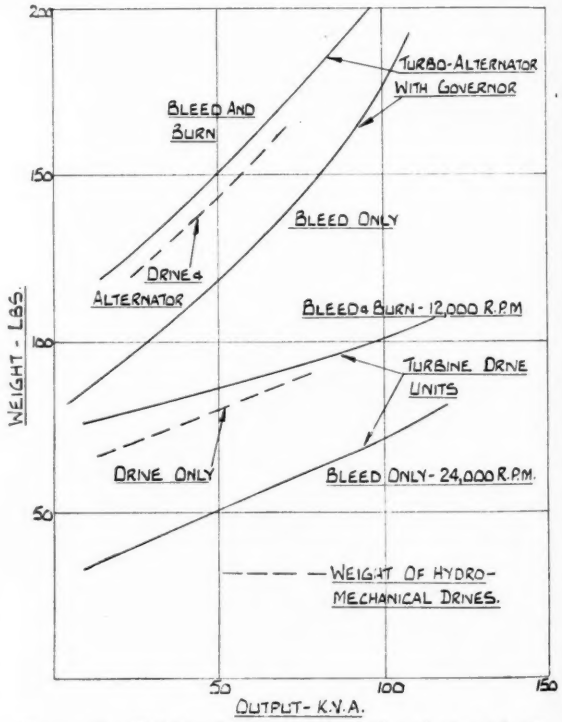
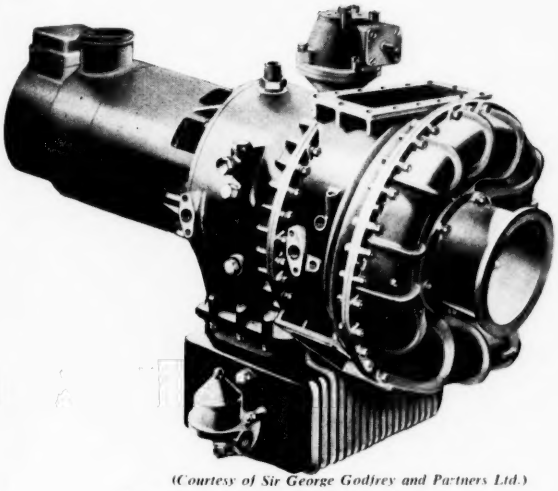


FIGURE 8. Weight of hydro-mechanical and air and gas turbine drives.



(*Courtesy of Sir George Godfrey and Partners Ltd.*)

FIGURE 9. 15 k.v.a. air turbine drive.

normal cruising and if the wheel speed is thus selected, both a low output and a poor efficiency are obtained at lower aircraft speeds.

As will be seen from the curve, a lower turbine wheel speed is of some help in dealing with low pressure ratios associated with descent under idling conditions, although a small penalty is paid by increased air consumption at cruising speed.

It has been said that idling speed will have to be increased to meet operational requirements generally and, if this is so, the difficulty with the air turbine under this condition will be eased. An alternative approach would be to employ a two-speed gear between the turbine and the final drive shaft, so that a lower wheel speed is employed for idling descent case, using the high speed ratio to economise in air at normal cruising. Such an arrangement would help a great deal under the landing condition.

To assess the weight penalty associated with air turbine drives, it is necessary to consider specific aircraft, their flight plan and their minimum ancillary power requirements under the various conditions of flight.

As with other drives, it seems essential that realistic load figures are utilised when the sums are worked out. It does seem that the requirements demanding full power over an engine speed range of 3·5 to 1 are not always necessary and can lead to severe weight penalties if slavishly adhered to.

3.1.2.3. *Gas turbine motors*

To reduce fuel weight or aircraft range penalties associated with air turbine motors, gas turbine motors have been developed in the U.S.A. and work is also proceeding on this project in this country and, as electrical power demands increase, it appears to offer an attractive means of obtaining a constant speed drive.

Basically, this type of motor employs a "hot" wheel, bleed air being taken from the engine compressor, as with the air motor, but being mixed with fuel and burned in an integral combustion chamber. Thus the bleed air requirements are substantially less than with the air motor for a given output power.

The weight of the unit itself is naturally somewhat higher than that of the equivalent air motor and Fig. 8 shows some estimated weight figures. There are good grounds for believing that, with development, the gas turbine motor, with its reduced air consumption, can show an overall weight saving over other drives, particularly for the larger alternators envisaged.

3.1.2.4. *Hydraulic drives*

Where space considerations prevent the use of a self-contained hydro-mechanical drive, there is a split-type hydraulic drive in which, unlike the hydro-mechanical drive, all the power is transmitted by oil. This envisages a hydraulic pump mounted on, and driven by, the engine and a hydraulic motor driving the alternator or other ancillary unit, the pump and motor being coupled by pipes.

Naturally, both the hydraulic units have to be larger than those used in the self-contained drive, and it is therefore much heavier, but the split hydraulic drive has the advantage over the air or gas turbine motor in that the hydraulic motor-alternator unit can be mounted remotely from the engine and, when desirable, in close proximity to the busbars. Heavy cable between the engine and the busbars can therefore be avoided, but oil pipes, with their attendant losses, must be substituted.

3.1.2.5. *Hayes drive*

The Hayes variable speed transmission provides a mechanical solution to the problem of obtaining constant speed output for alternator drives. The unit is of the mechanical friction drive type, employing rollers loaded between toroidal shaped discs and whose angular position is changed to vary the speed. The principle is an old one and has had many years development, so that it now represents probably one of the most advanced types of friction drives at present available.

The important features in a friction drive unit are that torque should be equally transmitted by the component members and that the loading applied to these members should be proportional to the torque applied. These features have been built into the Hayes unit.

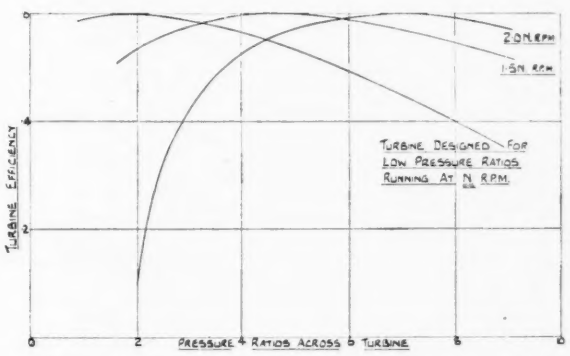

2 DM.EPH
1·5N RPM
TURBINE DESIGNED FOR LOW PRESSURE RATIOS RUNNING AT N R.P.M.
TURBINE EFFICIENCY
PRESSURE RATIOS ACROSS TURBINE

FIGURE 10. Efficiency of air turbine against pressure ratio.

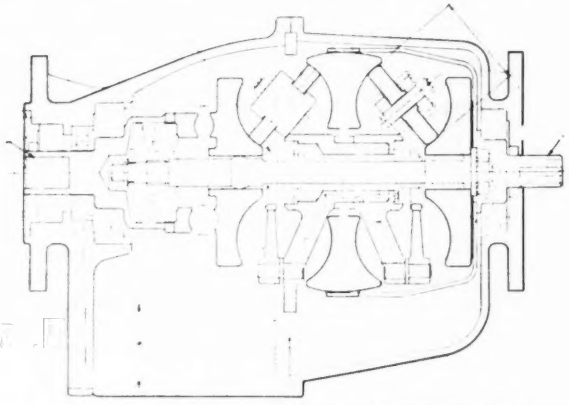
The Hayes has special advantages for use in constant output speed applications in that the drive is co-axial to the gear and a special means of ratio change allows for a small angular movement of the controlling member to cover the full ratio range. The important feature in a friction drive transmission is that the driving members should have reasonable rolling characteristic and here, too, the Hayes benefits, the form of rolling being analogous to that found in an angular contact ball bearing.

Past experience in automobile application and in some industrial applications shows that the gear is robust, durable and efficient. Recent tests show that a unit, approximately as shown on Fig. 11 and measuring approximately 16 in. long × 12 in. × 12 in., should be capable of driving a 30 k.v.a. alternator at 8,000 constant r.p.m. with an input variation of 3,000 to 10,000 r.p.m. From the endurance tests the efficiency of this unit will average 85 per cent. and the minimum anticipated life is 500 hours. As the unit is analogous to a ball bearing from life capacity point of view, the average anticipated life should be approximately five times the minimum anticipated life.

To obtain constant output speed, governor control will be applied through a hydraulic servo-motor taking its oil from the transmission lubricating system. The transmission may either have its own sump and lubricating arrangements, or it may be coupled to the aircraft engine oil system if required.

The Hayes unit will show some special advantages in providing a solution for constant frequency power in that it does not require exceptional accuracies in manufacture, the unit envisaged having tolerances no finer than ±0·001 in., nor does it require exceptional skill and training either in assembly or in maintenance. Further, the members which will suffer the most wear—that is the rollers—can be replaced easily and cheaply and the discs with which they are in contact can be reground at least twice before being completely unusable.

To summarise, it might be said that the Hayes unit provides a straightforward means of producing constant output speed from a varying input speed when



(Courtesy of Tilman Langley Ltd.)

FIGURE 11. Hayes transmission. 3,000-10,000 r.p.m. input. 8,000 r.p.m. output. 30 k.v.a. alternator drive.

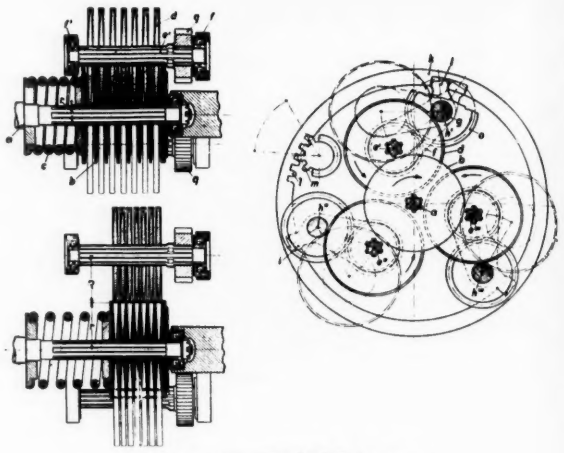


FIGURE 12. Typical Beier gear.

governor-controlled; is easy to manufacture and maintain; provides a useful speed range, six to one at maximum; and incorporates refinements which considerably aid efficiency and endurance capacity.

Weight estimates for the finalised unit are not yet available.

3.1.2.6. *Beier infinitely variable gear*

The Beier infinitely variable gear, which has been developed on the Continent for industrial purposes, has been considered as a constant speed drive unit for aircraft purposes.

The outstanding feature of this gear is that the power is transmitted through the drag force in thin films of oil, temporarily of very high viscosity, interposed between the driving and the driven members. There is therefore no metallic contact between these members, which consist of a number of thin conical discs and a corresponding number of thin discs with flanged edges. As many discs can be used as may be necessary to transmit any given amount of power, or to suit any specific purpose. The film of oil between the discs is constantly renewed by the rotation of the discs and temporarily subjected to high pressure, which raises its viscosity many thousandfold. This high viscosity provides a powerful drag force in the oil film, by means of which power can be transmitted.

Several small industrial units have been tested and a design suitable for a 30 k.v.a. alternator has been evolved. In addition, this type of gear is used by one of our engine constructors for another purpose, with success.

It is estimated that for larger sizes, the power-weight ratio would be slightly more than one h.p. per pound.

A sectional view of a typical Beier gear is shown in Fig. 12 and Fig. 13 shows the proposed 30 k.v.a. model, the estimated weight of which is 45-50 lb.

3.1.2.7. *Auxiliary power units*

At one time it was thought that generation of ancillary power for aircraft purposes should be divorced from the main propulsion engines of the aircraft and

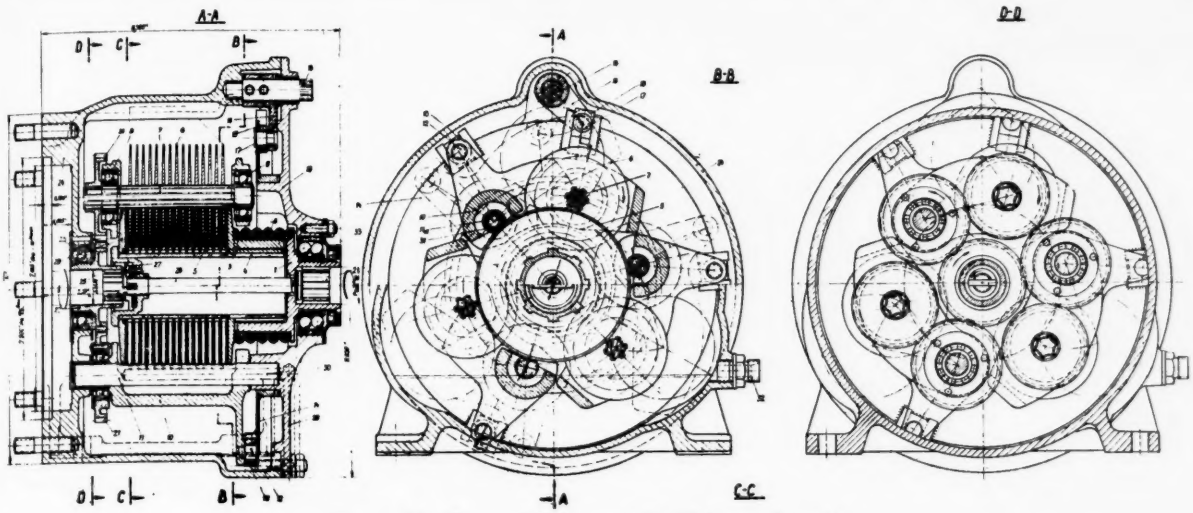


FIGURE 13. Proposed Beier gear for 30 k.v.a. alternator.

that separate auxiliary power units installed in a "power house" should be used.

It will be remembered that power generation for the Short "Shetland" aircraft was provided by means of two petrol-engine-driven alternator-cum-d.c. generator sets.

At first, such a scheme looks attractive for the large aircraft, since it centralises the ancillary power system, makes it completely independent of the main engines and permits certain maintenance to be done in flight.

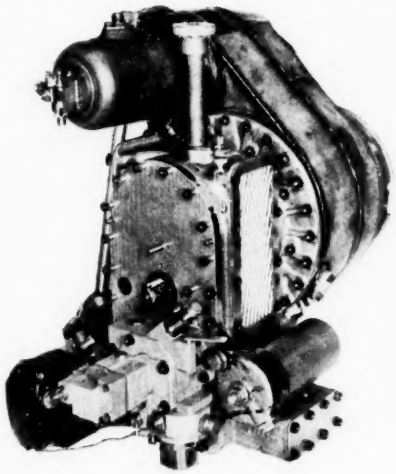
In addition, an auxiliary engine with speed control can furnish an ideal drive for an alternator for a constant frequency system, but more recent investigations show that, although such units are attractive for emergency and other purposes, there is no real argument at the present time for using them for main supply generation.

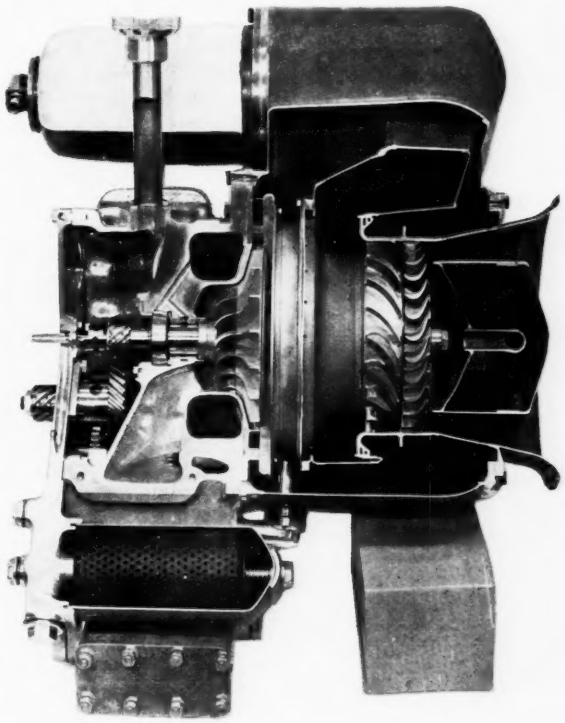
To be attractive, the auxiliary power units, and they would undoubtedly be small gas turbines, should have a power-weight ratio, including fuel, comparable with that of the main engine plus its constant speed drive. This cannot be achieved with the small gas turbines now available. If alternator capacities are increased, as predicted, such units may become more attractive.

It is certain, however, that small gas turbines giving shaft power, and small gas turbine compressors giving bleed air, will prove useful, not only for starting purposes, but also for giving emergency power for essential loads in flight.

3.1.2.7.1. *Rover gas turbine engine* 1S/60

This engine will give 60 h.p. at zero forward speed and sea level, with a fuel consumption of





FIGURES 14 and 15. Rover gas turbine type 1S/60.

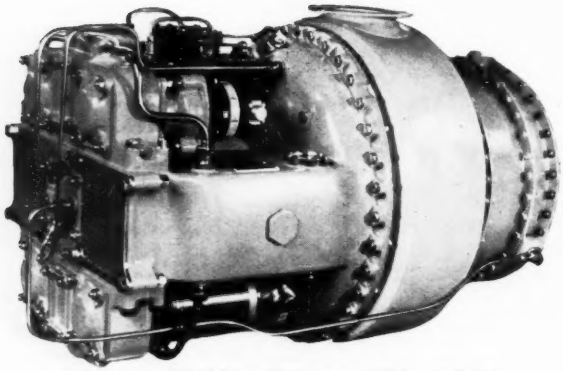


FIGURE 16. Blackburn Turbomeca "Palouste" gas turbine compressor.

1·4 lb./b.h.p./hr. The bare engine weight is 116 lb. With 500 m.p.h. forward speed and 50,000 ft. altitude, the power under I.C.A.N. conditions would be about 28 h.p. Such a unit is therefore capable of providing emergency power in flight.

As an alternative, the Rover engine can be used as a producer of bleed air and at sea level will give 0·6 lb. of air per second at 39 lb./in.^{2} absolute, which is sufficient air for 28 h.p. to be developed by an air turbine motor. This would be sufficient for the starting of several of our largest turbines. Furthermore, in the course of development, the compressor can be increased in size, so that an air output to drive an air turbine starter of 40 h.p. should be possible.

If used as a bleed air unit in flight, 12 h.p. would be available at 40,000 ft. and 7 h.p. at 50,000 ft.

The Rover gas turbine is shown in Figs. 14 and 15.

3.1.2.7.2. *Blackburn turbine engines*

The " Palouste " is a gas turbine compressor unit of rather larger capacity. It is capable of delivering 2·725 lb. of air per second at 40-50 lb/in^2 abs. at sea level. It is therefore capable of supplying the requirements of air turbine starters suitable for the largest engines envisaged. Although the performance at high altitude is not known, it should provide enough for emergency power requirements. The weight of the " Palouste " is 178 lb.

The "' Artouste " 500 is a single shaft drive unit in the same range of engines and this will give a sea level power of 345 h.p.

These small turbines are shown in Figs. 16 and 17.

3.1.3. *Alternators*

Future alternators will be designed with constant speed applications in mind. Speeds will probably be standardised at 8,000, 12,000 and 24,000 r.p.m.

Experimental units are being made to run at 24,000 r.p.m. and, if satisfactory, they will have application with air or gas turbine motor drives, since it will probably be possible in such cases to eliminate all gearing between the drive unit and the alternator.

By use of suitable materials, which will be dealt with later, it is hoped that maximum operating

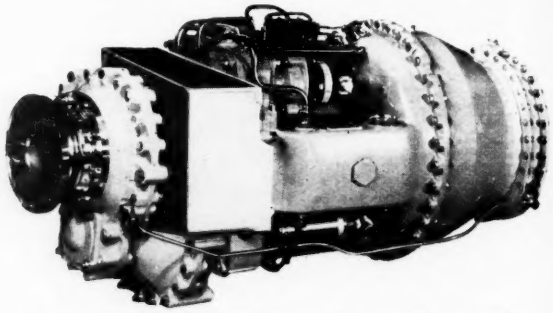


FIGURE 17. Blackburn Turbomeca "Artouste" gas turbine.

temperatures up to about 300°C. will be possible. Oil lubrication will be necessary. Built-in exciters may be desirable, and if suitable rectifiers are available, small alternators will be used for this purpose.

3.1.3.1. *Brushless alternators*

It is obviously highly desirable to eliminate brushes and sliprings, so that further consideration should be given to the development of brushless alternators.

Alternators without d.c.-excited rotors can be designed in five distinct types:

(*a*) Permanent-magnet rotor type.
(*b*) Induction type.
(*c*) Inductor type.
(*d*) Cascade type.
(*e*) Rotating rectifier type.

The first three types have been examined in the past and have not been considered suitable because of low power-weight ratio and other limitations. However, these types of alternators were reviewed as variable frequency machines and a further study may be worth while.

The double armature cascade alternator was thought at the time to be more promising and a considerable amount of design work was done on this type of alternator. Fig. 18 shows the basic principle of this type of machine, which is of twin rotor and stator type, originally due to C. S. Bradley[4]. The exciter part of the machine is a salient pole alternator with d.c.-excited stationary field and rotating armature wound for three phase output. The armature currents in this part create a practically sinusoidal flux which is stationary in space. The output currents are fed into the rotor of the other part of the machine, but their phase sequence is reversed, so that, assuming the flux is rotating clockwise relative to the rotor in the exciter, the flux in the generator part is rotating anti-clockwise relative to the rotor. The sense of rotation of the rotor for this condition is anti-clockwise because the flux of the d.c.-excited part is stationary in space and therefore the flux of the right-hand machine rotates anti-clockwise relative to its stationary armature.

Naturally, such machines are heavier than conventional alternators, but the absence of brushgear and sliprings is such an attraction that further thought will have to be given to constant speed alternators of this type.

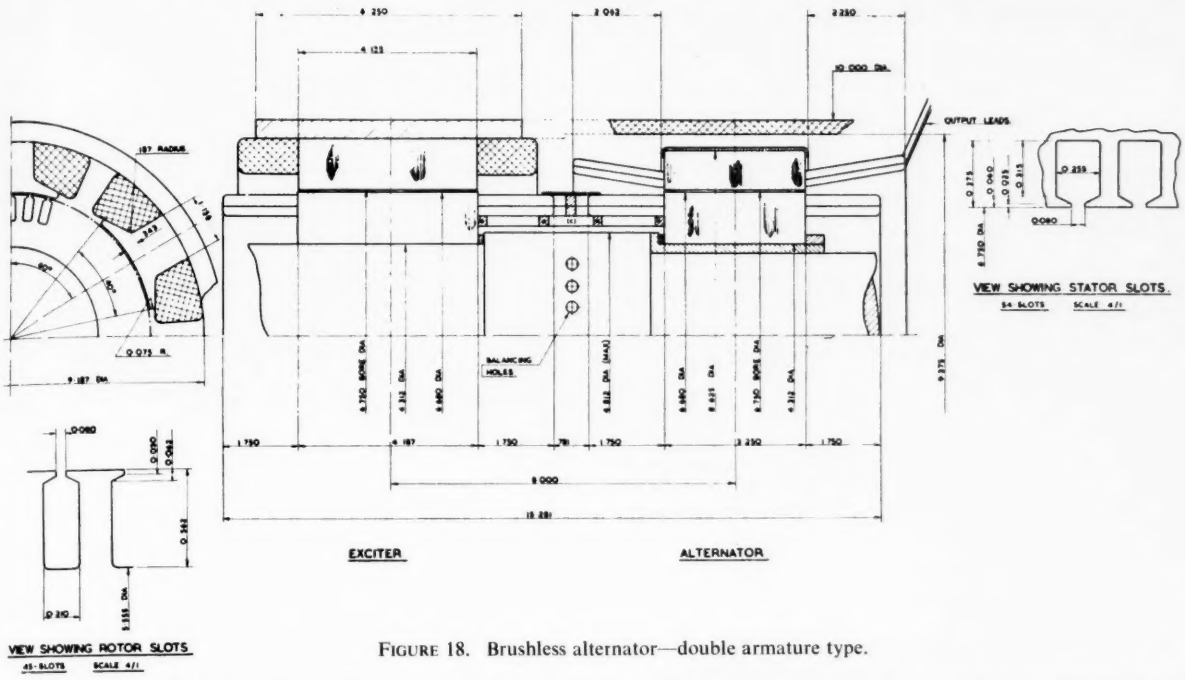


FIGURE 18. Brushless alternator—double armature type.

Another type of brushless alternator which has recently been considered in the U.S.A. is one in which the alternator has a built-in exciter, consisting of a smaller alternator with rotating armature. Current from the exciter armature is fed to the main alternator field through silicon rectifiers, which rotate with the shaft.

A similar construction was thought of in 1939 and covered by British patent (Fig. 19[6]) but it was not a practical proposition with the rectifiers then available. The use of very small silicon rectifiers has made possible this latest American design and the importance of the semi-conductor development will be emphasised elsewhere in the paper.

3.1.4. *D.C. systems*

D.C. systems, both of low voltage and medium voltage, will be with us for some years and it may be that the low voltage d.c. system will always be retained for fighters, helicopters and, perhaps, for twin-engined medium-range aircraft.

If the loads on fighter aircraft rise to the figures forecast earlier in the paper, then it is likely that, in addition to 400 amp. d.c. generators, fighter aircraft will have to carry alternators, and it is suggested that these cover heating, radio and radar loads. The possibility here is for the air turbine drive, so that constant frequency a.c. will be available, permitting the elimination of all inverters.

It is not thought that there will be any radical changes in the design and construction of d.c. generators to cover a wide speed range, other than by use of improved materials to increase efficiency and reduce weight and to uprate them from the temperature angle.

It is, however, put as a suggestion that constant speed drives can be attractive for d.c. machines. Certainly some weight saving could be effected by driving them by this method and, in addition, commutation will be more consistent and likely to withstand more easily the onerous conditions imposed by the latest type of impregnated brushes. In addition, voltage regulator problems are somewhat eased.

3.1.5. *Switchgear*

Here again, increasing altitudes and higher ambient temperatures will present problems. For instance, above 50,000 ft., further work will have to be done to

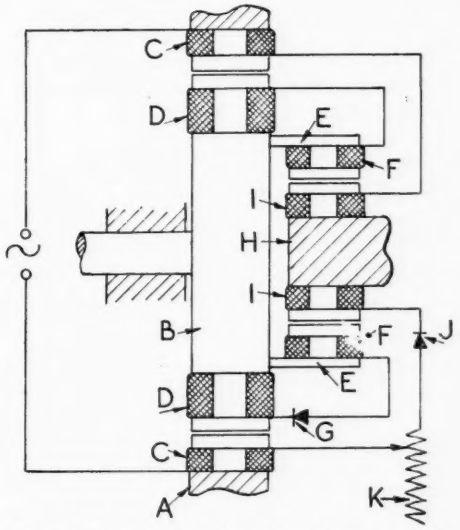


FIGURE 19. Principle of brushless alternator with rotating rectifiers.

improve arc rupturing, particularly in systems for 112 volts d.c.

Arc quenching by means of simple de-ion grids, which are energised by the magnetic field surrounding the arc, has proved to be satisfactory by existing applications, but with increased generator capacities and the higher short circuit currents which are likely to be encountered, it is almost certain that a more complex arrangement, consisting of arc runners, series magnet coils for moving the arc along the runners, and a magnet coil for de-energising the de-ion grids, will be required.

Other methods for dealing with the problem of altitude operation are being considered, including the use of completely sealed units, but much work has still to be done, particularly on units of large current rating where the sealing of heavy conductor members becomes difficult from both a technical and economic viewpoint, unless the degree of reliability can be made so high as to preclude the need for servicing throughout the life of the unit.

To ensure satisfactory and reliable operation of circuit breakers and contactors of the remotely controlled type over the wide range of ambient temperature now foreseen, it is certain that many of the existing methods of operation and construction will require considerable modification. It would appear to be necessary, to avoid further increases in working temperature due to self-heating of the operating coils, to abandon the use of continuously energised magnet coils now used in many applications, in favour of the impulse energised type with mechanical latching. Some wide range temperature resistance compensation of these coils will be necessary to avoid the possibility of mechanically over-loading the contact closing mechanism when operating at low temperature, with resultant contact bounce. It appears likely therefore that some weight penalty over existing designs must be expected.

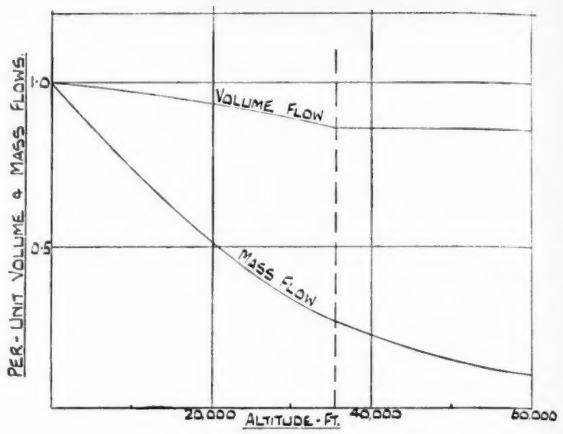
The design trend will be towards the greater use of fabricated or cast metal housings for the contact assemblies, insulated where necessary by means of suitable high temperature resistant materials, instead of the housings being moulded in insulating material as at present.

The design of thermal overload trip gear will require much attention and it may be found necessary to use means other than bimetal strips for operating the trip devices, as much of the bimetal material in common use offers a serious loss of load capacity and deflection sensitivity at temperatures very little in excess of those now considered to be working temperatures.

Ambient temperature compensation of such devices will almost certainly be required if adequate protection is to be given to the circuits or apparatus throughout the temperature range.

3.1.6. *Actuators*

As with other components, actuators will have to be developed to meet the increased temperature conditions which will be encountered.



$$\frac{V_A}{V_O} = \sqrt{\frac{T_A}{T_O}} \text{ and } \frac{m_A}{m_O} = \sigma\sqrt{\frac{T_A}{T_O}}$$

Where: V_A = Volumetric flow at altitude
V_O = Volumetric flow at sea level
m_A = Mass flow at altitude
m_O = Mass flow at sea level
T_A = Absolute temperature at altitude
T_O = Absolute temperature at sea level
σ = Relative density
Based on I.C.A.N. tables.

FIGURE 20. Air flow *versus* altitude at constant Mach number.

This is probably more difficult to achieve with small d.c. motors than with large generators and motors. A fundamental feature of high temperature operation is the complete elimination of soft solder and the substitution of brazing and welding for electrical connections. With very small d.c. armatures, definite problems exist, but these are being dealt with by suitable methods of construction.

The problems associated with small a.c. motors of the squirrel cage type are not so acute. Furthermore, the life of such units before maintenance is required should be considerably longer than the life of small d.c. motors.

An a.c. linear actuator with high efficiency screw and nut will represent a big step forward and development work is going ahead on such projects.

3.2. COOLING

For aircraft operating at supersonic speeds, it is essential that maximum temperatures of equipment be raised by the use of improved materials. It is suggested that this figure can be as high as 250°C. in the not too distant future, and at this temperature ram-air cooled equipment would be satisfactory up to about a Mach number of 1·5 at 50,000 ft. Fig. 20 shows the relationship between mass-flow and altitude when flying at a constant Mach number; the mass-flow in this case is proportional to σV, where V is the true air speed.

These conditions are illustrated in Fig. 21; the inlet temperatures are based on I.C.A.N. conditions plus adiabatic heating and, because of the rapid drop in mass-flow with rising altitude, the permissible G.L. rises for corresponding altitudes are severely reduced.

Thus over-cooling at low levels is necessary and the drag would be appreciably increased. At a Mach number of 2 the inlet temperature at G.L. reaches 249°C. and to achieve cooling at this speed, maximum machine temperatures of 300°C. would be necessary.

Alternatives to ram air for the cooling of electrical equipment will have to be considered very seriously, but uprating of machine temperatures will go a long way towards reducing the weight of cooling equipment and the drag penalty associated with it. It has been stated in an American paper[6] that in one particular instance an increase in component temperature from 130 to 160°F. was responsible for the elimination of a separate cooling system weighing 100 lb., and the substitution of a ram-air system weighing 50 lb. The drag horse-power was reduced from 100 to 10.

New methods of cooling equipment will ultimately be necessary and these should be investigated on a high priority. If air is used at the heat sink, then this air will have to be cooled through an expansion turbine and used through a heat exchanger to cool the primary coolant circulating through the machine.

Alternatively, compressor bleed air can be employed for cooling the machine directly, and this is current practice on certain present-day aircraft, but due to the higher temperatures of the bleed air under certain flight conditions, this will not give satisfactory cooling to as high a Mach number as direct ram air, assuming a constant mass-flow. However, this bleed air could be cooled through a turbine, a ram-air to bleed-air heat exchanger being used and a separate compressor to dissipate the turbine power.

Evaporative systems can be employed and may have particular application on fighter aircraft on short missions, since the heat removed per gram of coolant is very high and, with water, it is more than ten times the figure obtained with a direct recirculating liquid cooling system.

Perhaps the most promising liquid cooling system is one employing engine oil as the primary coolant, and engine fuel as the heat sink.

Already alternators employing this type of cooling

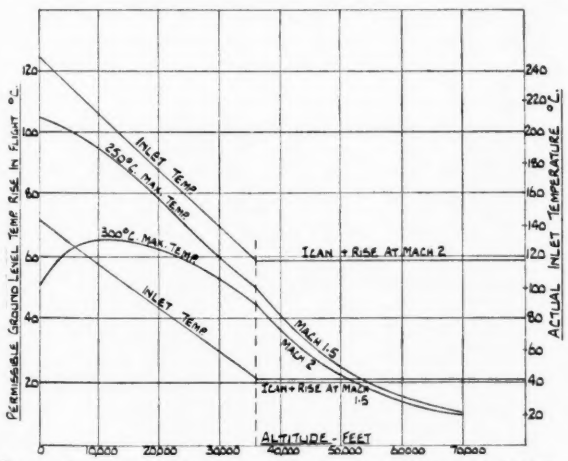


FIGURE 21. Sea level temperature rise for 250°C. and 300°C. maximum temperatures.

are being developed in the U.S.A. The use of oil for cooling ties up very well with the necessity for oil for bearing lubrication. The combination of this type of cooling and bearing lubrication with the brushless type of alternator, eliminates the difficult sealing problem which would arise if brushes and sliprings were present. With the outlined arrangement, it is claimed that the presence of free oil or oil vapour is not detrimental to the operation of the machine.

The cooling oil is introduced into the alternator shaft to cool the rotor and also flows through circumferential slots in the stator frame.

In the discussion on high stagnation air temperatures and cooling of electrical equipment, emphasis has been given to conditions arising during high speed flight at high altitudes. At low speeds and at lower altitudes than specified, conditions can be worse from the cooling angle. Flight plans for supersonic aircraft are not yet known and it seems necessary for specifications to be evolved showing maximum and minimum speeds, altitudes and approximate duration of flight under these conditions, if equipment designers are to put forward designs of minimum weight and efficiency.

3.3. METHODS OF INCREASING OPERATING TEMPERATURES AND EFFICIENCY AND REDUCING WEIGHT

3.3.1. *Materials*

Equipment will be uprated as far as temperature is concerned by use of improved materials. Insulating materials will play the most important part in this. As has been stated, present-day organic insulating materials are satisfactory up to a maximum temperature of 170 or 180°C. These include conductor coverings in the range sold as "*Lewmex*," "*Formvar*," "*Conymel*" and others. Fibre-glass insulation is only as good as its insulating varnish, and with the best of these now becoming available, 200°C. appears to be the maximum operating temperature. Using this latest varnish for conductor coverings, with or without fibre-glass, and with mica-glass slot lining, continuous running at 200°C. maximum temperature should now be possible as far as windings are concerned.

If solid moulded brush rings are used, Alkyd resin mouldings are satisfactory up to about 160°C. For 200°C. and over, Mycalex and Micalon inorganic mica-glass mixtures are promising. They have no temperature limitation but are inclined to be brittle. Silicones-bonded glass fibre mouldings are also promising for temperatures up to 250°C.

For 200°C.—300°C., the use of P.T.F.E. as a covering for copper strip and wire is one of the more promising lines of attack, and work is proceeding to develop this type of covering. Because of the low plastic yield of P.T.F.E., some glass reinforcement will be necessary.

With alternators, it may be possible to use mica without an impregnant for insulating both rotor and stator windings, but considerable development work will obviously be necessary.

The silicones range of materials have not yet been proved to be up to the original claims put forward

some years ago. Not only do they suffer because of high moisture absorption, but they appear to have a rather low bond strength. There is no doubt that insulating varnish plays a dual role, one of eliminating air space between conductors, and the other of assisting the retention of the conductors in their slots and field coils on their poles.

Silfos brazed or welded connections are now commonplace on aircraft equipment and these will cover the maximum equipment temperatures foreseen.

Reduction in weight of equipment is possible by increased use of magnesium alloys and titanium, and by improved magnetic materials. Titanium or one of its alloys, although costly, will be used with advantage in place of steel for shafts and a number of other components associated with starters, actuators, and so on. Low Moor "*Purefe*" represents a substantial improvement over previously available iron for generator yokes and relay magnets.

Permendur is now being used for d.c. generator poles and alternator stators, and use of a 25 per cent. cobalt iron alloy for armatures is being investigated. Permendur (50 per cent. C_o 50 per cent. F_e) can show up to 5 per cent. reduction in machine weight if used for yokes and poles.

3.3.2. *Components*

3.3.2.1. *Rectifiers*

Rectifiers are extensively used on present-day aircraft and although the introduction of a.c. constant-frequency systems would obviously reduce the number required, they will still play an important part in radio, radar and other equipment.

It is therefore necessary to find a substitute for selenium, the maximum operating temperature of which is about 100°C.

Silicon looks to be the most promising of the semiconductors which are now being developed, both in this country and the U.S.A. In the U.S.A., certain silicon diodes are already available and it is claimed that they are satisfactory at 200°C. Tests on some sample units from the U.S.A. will shortly be made.

It is of paramount importance that this development proceeds over here with the highest priority. Without it, the exercise of uprating machine and equipment temperatures cannot be finalised.

Silicon transistors, which could ultimately replace the magnetic amplifiers associated with voltage, frequency and temperature control units, and save weight and space, should also have the attention they deserve.

3.3.2.2. *Condensers*

Present-day paper condensers, particularly those of the high voltage type, are unsuitable for high temperature operation. Here again, a new approach is necessary, and both P.T.F.E. and Mylar, which is a film made from Terylene, are being considered as the dielectric in place of paper.

It appears that for certain duties, such as the high energy ignition unit in which a 6 mfd. condenser is charged to 2 kv., some increase in the volume of the condenser may be necessary.

3.4. BATTERIES

Aircraft batteries of the lead-acid type have been subjected to criticism for many years, mainly because of their short life and poor power-weight ratio.

There would appear to be some ground for saying that battery development over the past 20 years has hardly kept pace with the development of other electrical accessories. To be fair, there were some important contributions towards the reduction in the weight and the reduction in the internal resistance of the lead-acid battery during the Second World War. Joint efforts of the R.A.E. and British battery manufacturers were responsible for the introduction of batteries having thinner plates and porous ebonite separators and such batteries had better characteristics at lower temperatures than batteries of earlier design.

Nevertheless, research into fundamentally new types of batteries has not had the attention it deserved.

During the post-war years, France and the U.S.A. appear to have led the field in an attempt to develop aircraft batteries eliminating both lead and acid, but a very important British contribution has been made in weight and size reduction by retaining lead, but dispensing with free electrolyte, an important point when considering batteries suitable for all attitudes of flight.

The French and U.S.A. efforts, which concern the silver-zinc battery and the nickel-cadmium battery, have each got to a production stage, but in neither case does the battery meet all the conditions found in flight and a considerable amount of further development is obviously necessary. At the same time, for certain specific applications, they do show several important advantages over previous lead-acid types.

The new British absorbed-acid type of battery may, in the long run, show more promise than the aforementioned types.

3.4.1. *Silver-zinc cell*

Due to Andre and Yardney, the silver-zinc battery was originally developed in France. It uses silver-oxide positive plates and zinc negative plates with a potassium hydroxide electrolyte. It is characterised by an excellent power-weight ratio which, for a given capacity, is double that of the best conventional lead-acid type. Certain types of silver-zinc batteries are now produced in England.

Its chief disadvantage lies in the fact that for its complete charging, a low-rate constant-current charge is essential. With present low-voltage systems regulated at 28·5 volts, the battery does not become completely charged. Slight increase in system voltage increases the percentage re-charge in a given time; such an increase, even if acceptable by the apparatus on the busbars, can lead, under high ambient temperature conditions, to high initial load on the generator. Further, increase in system voltage can lead to severe damage to a warm battery.

Thermal devices which switch off the charging current at a predetermined battery temperature are being tried out.

The other disadvantages of the silver-zinc battery

are poor characteristics at temperatures below 0°F. when discharge currents are of the order of 200 to 400 amperes and first cost. Built-in heaters are being considered to combat the former disadvantage.

At present, the main use of the silver-zinc batteries is for guided missiles and other applications where charging in flight is not required. One typical use is for starting purposes on a jet fighter destined for short missions.

Some practical tests have been made on silver-zinc batteries of French make. The battery tested was of 40 amp.-hour capacity and the weight was 39·5 lb. This compares with the existing 40 amp.-hour M.O.S. lead-acid battery, which weighs 73 lb.

From a fully-charged battery, it was possible even with the battery at 0°C., to obtain over 20 satisfactory starts and cranks of a large turbine engine. This illustrates that, despite its disadvantages, the silver-zinc battery can be used for engine starting under specific conditions, and with considerable weight saving.

3.4.2. *Nickel-cadmium cell*

Nickel-cadmium batteries were used by the major British airline operators before the 1939-45 War and were favoured because of their long life and their ability to withstand accidental short circuit without serious damage.

They were, however, considerably heavier than the current lead-acid batteries. In addition, their high internal resistance was such that it was difficult to use them for starting purposes.

The new nickel-cadmium battery as produced in France and the U.S.A. is improved by the use of sintered positive plates and by the packing of more plates into a given container, thereby increasing its power-weight ratio and reducing its internal resistance to figures comparable with present-day lead-acid types. Its main feature is that it is a completely sealed unit, which does not require electrolyte replacement during its life. Under high ambient conditions and discharge currents of more than 50 amperes, its kilowatt-hour capacity is rather higher than that of conventional lead-acid, but it is slightly inferior at 0°F. and below.

There is, as yet, no practical experience of this battery in Great Britain, but some practical tests will be made shortly.

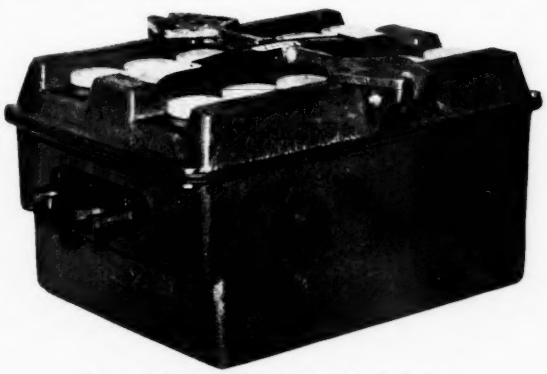


FIGURE 22. A Varley 24 volt 25 a.h. battery.

3.4.3. *The absorbed-acid lead battery*

This is a British development by the Varley Company and is of great interest. Light weight and low internal resistance for a given capacity are obtained by use of very thin plates of high porosity supported and maintained under compression so as to form a tight pack. The separators are of a special material, completely acid resisting, being chemically similar to ordinary sand and having highly absorbent characteristics. Thus the electrolyte is completely absorbed in the pack, there being no free acid.

It is claimed that this type of battery is unaffected by vibration. It is also stated that this battery does not exhibit the "run-away" characteristic associated with other types of batteries.

A 25 amp.-hour battery of this type is shown in Fig. 22. This battery weighs 37½ lb. fully charged, and on short time discharges at normal temperature has one volt drop per 62 amperes, compared with one volt per 80 amperes for a 40 amp.-hour conventional lead-acid battery.

If the present Varley battery were increased in size to give the same droop as the present standard lead-acid type, it would still be very attractive for engine starting purposes and for other duties, particularly those associated with high discharge currents for short periods.

3.5. TRENDS IN ENGINE STARTING SYSTEMS

Starting systems are covered by two distinct specifications, one calling for a self-contained starting system and capable of giving a quick start (10 seconds to engine idling) and primarily required for military fighter and similar aircraft, and the second for multi-engined military bomber and transport aircraft and civil transport aircraft, for which a quick start is not required. In these cases, times of 20 to 30 seconds are usually accepted for the starting to idling. In the military cases, self-contained starting equipment is demanded, while civil airline operators are not unanimous in their opinion, some asking for self-contained starting, and others, who are not prepared to accept the weight penalty involved, using a ground supply unit.

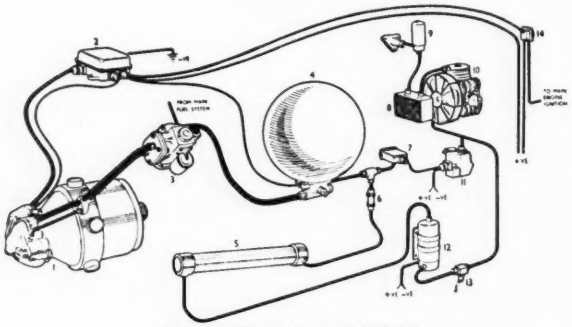
3.5.1. *Starters for quick starts*

Superseding cordite-operated starters, which have been used for the last few years, two types of liquid-propellant starters are being developed, one using aviation fuel with air, and the other a mono-propellant known as iso-propyl nitrate.

Figures 23 and 24 show these two systems. There is little to choose between these systems for weight and they are both capable of further development.

The fuel-air system uses any normal aircraft fuel and makes use of a small turbine which is accelerated to a high speed by the gases of combusion of a fuel-air mixture. An air compressor and an air storage bottle are necessary adjuncts to this system.

Iso-propyl nitrate starters are of similar basic type, but use gases produced by the decomposition of this fuel when subjected to heat and pressure. This starter requires a tank to contain the special fuel, and an electric motor-driven pump.



KEY TO SYSTEM COMPONENTS

1. Starter
2. Ignition control unit
3. Air-fuel servo unit
4. Air storage bottle
5. Air drier
6. Air check valve
7. Storage bottle pressure switch
8. Air cooler
9. Reducing valve
10. Compressor
11. Unloading valve
12. Water separator
13. External charging valve
14. Pilot's starting switch
15. External charging valve (alternative position used when external source of dry air is available)

FIGURE 23. Fuel-air turbo-starting system.

The main advantages of the fuel-air system are the utilisation of fuel already in the aircraft, and its relative independence of the aircraft electrical system, 10 amperes being the maximum drain during the burning period of 3 to 6 seconds.

Iso-propyl nitrate systems take 100 to 200 amperes from the aircraft battery for 6 or 7 seconds.

It is thought that larger batteries may have to be carried with this system installed, in which case the weight picture might swing in favour of the fuel-air system.

The need for a high pressure air compressor with the fuel-air system has been criticised, but it may later be found that such a compressor is a necessity on a number of types of aircraft where air is required for guided missiles, and possibly for actuators for reheat nozzles and other engine ancillaries working in a high ambient temperature.

3.5.2. *Starters for multi-engined aircraft*

Electric starters have been used on all turbines and turbo-prop engines on multi-engined aircraft since these types of power plant were introduced.

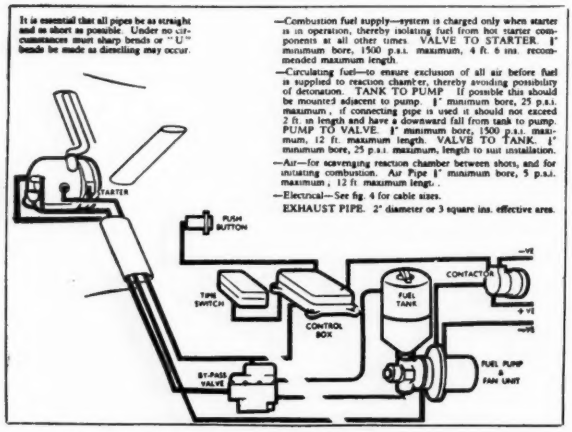

It is essential that all pipes be as straight and as short as possible. Under no circumstances must sharp bends or "U" bends be made as dieselling may occur.
—Combustion fuel supply—system is charged only when starter is in operation, thereby isolating fuel from hot starter components at all other times. VALVE TO STARTER. ¼" minimum bore, 1500 p.s.i. maximum, 4 ft. 6 ins. recommended maximum length.
—Circulating fuel—to ensure exclusion of all air before fuel is supplied to reaction chamber, thereby avoiding possibility of detonation. TANK TO PUMP. If possible this should be mounted adjacent to pump. ¼" minimum bore, 25 p.s.i. maximum, if connecting pipe is used it should not exceed 2 ft. in length and have a downward fall from tank to pump. PUMP TO VALVE. ¼" minimum bore, 1500 p.s.i. maximum, 12 ft. maximum length. VALVE TO TANK. ¼" minimum bore, 25 p.s.i. maximum, length to suit installation.
—Air—for scavenging reaction chamber between shots, and for initiating combustion. Air Pipe ¼" minimum bore, 5 p.s.i. maximum, 12 ft. maximum length.
—Electrical—See fig. 4 for cable sizes.
EXHAUST PIPE. 2" diameter or 3 square ins. effective area.
STARTER
PUSH BUTTON
TIME SWITCH
CONTROL BOX
FUEL TANK
CONTACTOR
BY-PASS VALVE
FUEL PUMP & FAN UNIT

FIGURE 24. Liquid propellant turbo-starting system.

112 volt d.c. starters are now available up to 60 horse-power. It is not recommended that low voltage starters be considered for powers greater than 12 h.p. if a self-contained starting system is envisaged. Because of the high currents demanded, the system efficiency is very much reduced and it becomes increasingly difficult to carry the battery and cable weight entailed.

Use has also been made of starter-generators in which a direct current generator is used as a motor for starting purposes, thereby eliminating the weight of an additional starter unit and drive.

Such units can be attractive, provided that the drive gear ratio can be common for both starting and generation. With the current type of 112 volt 22½ kw. generator, geared to give full generator output from 2,850 to 10,000 r.p.m., the unit gives adequate power as a starter for many of our present-day large turbines. The only doubtful point is whether the higher currents taken during the starting cycle will impair the condition of the commutator such as to reduce its life and that of the brushes when running as a generator. Work is being undertaken to check this point.

With generators of smaller capacity, their use as starters is not always easily achieved. In some instances the generator would have to be geared to give a very high top speed in order to retain a common drive ratio and give adequate starting power.

When aircraft systems become predominantly a.c., 400 cycle starter motors can be provided operating either from a ground supply or from an auxiliary turbine-driven alternator. However, it can be shown that the air turbine motor represents the lightest form of starting motor and in the future it is likely that this form of starter will be introduced on some types of aircraft.

Not only is the basic low pressure air starter considerably lighter than its electrical counterpart, but being practically independent of the aircraft battery, it has particular scope on aircraft with a predominantly a.c. supply, where it is hoped that battery capacities can be reduced to a minimum. Again, certain large military bombers will carry an auxiliary gas turbine and bleed air from this unit can be a convenient source of energy for the operation of these starters in a self-contained starting system.

Another method of obtaining a self-contained system is to use one or two fuel-air starters and two or three low-pressure air starters on a four-engined aircraft, the low pressure air starters taking bleed air from the compressor of the engine or engines already started by the fuel-air starters. Again, if it is desired to retain a large capacity battery, two electric starters and two low pressure air starters can be utilised, with substantial weight reduction.

For a ground-only start, a gas turbine compressor unit can be used to operate the low pressure air starters.

Any of these schemes show a marked weight saving over electric starting systems.

Figure 25 shows power plotted against weight for low pressure air starters and on the same curve is plotted the weight of electric starters of equivalent

powers. Air turbine starters have already been built and tested and Fig. 26 shows a typical starter. By their use on a four-engined aircraft with a constant frequency a.c. electrical system installed, and a small gas turbine compressor fitted, a saving of at least 120 lb. can be effected in the weight of the starting equipment.

Air starters can be designed to operate either from cold air at pressures up to 200 lb./in.^{2}, or from hot air (600°F.) at pressures down to 40 lb./in.^{2} absolute.

4. Conclusions

An attempt has been made to outline a few of the problems associated with aircraft electrical equipment which have to be solved within reasonable time.

It is suggested that the work involved in designing and developing equipment for supersonic flight should be attempted in several phases. The first phase might take us to a Mach number of 1·5 and the second to Mach 2 flight conditions, and the time when equipment is required to meet these phases should be laid down.

In addition, the material suppliers, who must play an important part in solving the problem of high temperature operation of equipment, should be brought into the picture and encouraged to develop high temperature insulating materials, and so on.

Furthermore, silicon or other high temperature semi-conductor rectifiers should be developed in this country on a high priority.

Summing up, the trends in electrical systems must be directed towards constant-frequency alternating current supplies, the equipment comprising such systems to be suitable for use on aircraft flying at a Mach number of 1·5 and 2·0.

Uprating of all electrical equipment from the temperature angle is very desirable, but study should also be made of all types of cooling systems.

Several types of constant speed drives must be developed, since it is quite impossible with available experience to choose any one type which has a marked superiority over the others.

It is suggested that air turbine motors, because of their light weight, should be considered for purposes

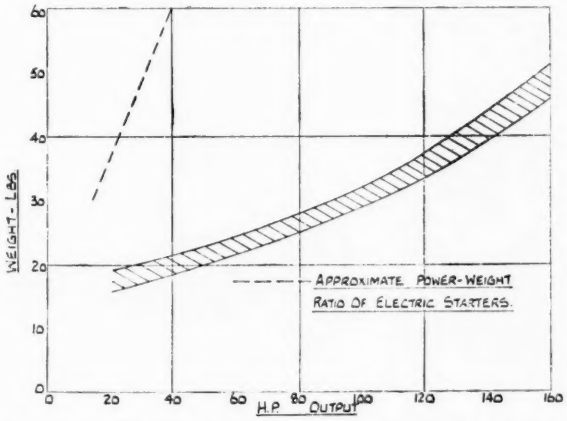


FIGURE 25. Power-weight ratio of low pressure air starters.

FIGURE 26. A Rotax 40 h.p. air turbine starter motor.

other than for use as alternator drives and engine starters. Already one air turbine motor delivering 3½ h.p. has been developed and this provides a useful drive for a high pressure air compressor or similar unit.

Actuators for undercarriage, flaps, and so on could also be thus driven, showing a weight reduction over other known types.

Further effort will have to be made to solve brush troubles now being experienced, particularly on d.c. machines.

Aircraft electrical engineers in this country are alive to the problems which lie ahead and, with support from the raw material suppliers and reasonable time for development, will provide the Industry with equipment to the required standard.

ACKNOWLEDGMENTS

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The Production of Large Forgings in Aluminium Alloys

by

C. SMITH, F.I.M. and J. CROWTHER, M.Sc., F.I.M.

(James Booth & Co. Ltd.)

Introduction

TODAY there is growing interest on the part of aeronautical engineers in forgings of large size, for three main reasons. Certain types of forgings will naturally need to be bigger as the aircraft itself becomes bigger; more composite structures are being replaced by single components made as forgings; and there is an increasing use of complex units machined directly from blocks of metal which are too big in at least one dimension to be made as extrusions or rolled plate. It is with these larger forgings that we are mainly concerned. Their production presents many serious problems. It is reasonable to hope that some of these will be overcome as experience grows and techniques are improved but others seem to be inherent in the materials used and must be appreciated at the design stage of the component if fully satisfactory service is to be obtained.

1. What is a Large Forging?

A forging is a piece of wrought metal which has been worked by the traditional methods of the blacksmith or some modern development of these. In open forging the metal is deformed by compression between a pair of tools (as between a hammer and an anvil) the power of the blacksmith's arm being replaced by that of a falling tup, often helped by steam or air pressure, or by a steady thrust from a hydraulic press. The traditional armoury of smithy tools is available for upsetting, drawing out, swaging, spreading and the like, in the conversion of the original cast or extruded stock of simple shape into a shape approximating externally to that of the component required and with the correct "grain flow" within the forging.

In die forging, the final shape is produced by squeezing the metal between a pair of shaped dies, by which process more complicated shapes may be produced and closer tolerances held on dimensions. The metal put into the die may be previousiy roughly shaped by hand-forging, by machining or sometimes by pressing in a pair of dies of simpler contour.

Having defined a forging it is perhaps necessary to say what constitutes bigness in a forging. Over the past few years there has been considerable discussion on big forgings in the Aircraft Industry, but it is perhaps still not sufficiently realised that bigness may be the expression of a number of quite different aspects of the forging, and that different sorts of bigness involve distinct problems to the manufacturer of the forging. The principal aspects to be considered are weight—or volume—dimensions and shape.

A forging may be big because it contains a great deal of metal and is therefore heavy. Purely on these grounds it is probably true to say that an aluminium alloy forging weighing more than 200 lb. must be regarded as a big forging. In this aspect of bigness the considerations which are critical are those of casting the original ingot from which the forging is to be made, and the heat treatment of the finished forging either before or after machining. Difficulties of forging procedure are not necessarily associated with heavy weight and the forging shown in Fig. 1, which weighed approximately 3,000 lb., presents no difficulties in forging technique and could be produced on a press of quite moderate size, say, 5,000 tons.

The second aspect of the forging which may constitute bigness is that of overall dimensions, which may necessitate the use of large plant solely on dimensional considerations, even though the weight of the forging does not of itself bring the forging into this classification. A forging of this type is a medium-sized airscrew blade weighing only 120 lb., but having an overall length of about 6 ft. The size of this one dimension necessitates the use of a relatively large press or hammer for its manufacture, although again the forging power required is not particularly high.

The third group of forgings which must be considered as big forgings are those which involve the use of very powerful plant, even though both their weight and their overall dimensions may be quite modest. Such cases arise where the shape required in the forging is such that the material offers very high resistance to deformation, and are particularly concerned with die forgings as distinct from forgings produced in open tools.

2. The Properties Required of a High Quality Forging

The aircraft designer specifies certain conditions which the forging must fulfil and of course, certain basic conditions must be agreed between him and the forging manufacturer before any forging can be produced. These are:—

(*i*) the basic shape of the component and the dimensional tolerances required in relation to the capabilities of the forging process,

A Section Lecture given before the Society on 15th March 1955.

(*ii*) The alloy to be used and the general level of mechanical properties required.

In addition, the designer and the production engineer expect other qualities to be present in the forging; often in the past this expectation has not been formally expressed by the designer and not anticipated by the manufacturer, with the result that forgings have fallen short of the ideal attainable. It cannot be too strongly emphasised that the best result will be achieved as a consequence of collaboration between manufacturer and user at an early stage in design.

These additional qualities include:—

(*i*) adequate strength throughout the forging and not merely in certain favourable positions. This should not (and in most cases cannot) mean the same strength in all directions in all positions of testing, but rather that the design allows for some inevitable variation of properties in the material which it is the manufacturer's duty to hold to a minimum. Designers are now much more informed on directional effect in working and mass effects in heat treatment.

(*ii*) virtual absence of flaws in the finished component. There are two aspects of this problem. Inspection of the surface of the finished machined component by chromic acid anodising is standard for aircraft use and the elimination of blemishes in the surface is generally straightforward although often very troublesome to the manufacturer. A more recent development is the request for forgings and forged machining stock to be examined by a non-destructive test such as by ultrasonic methods and the level of "defect" occurrence guaranteed, a development which calls for a careful and somewhat wary approach.

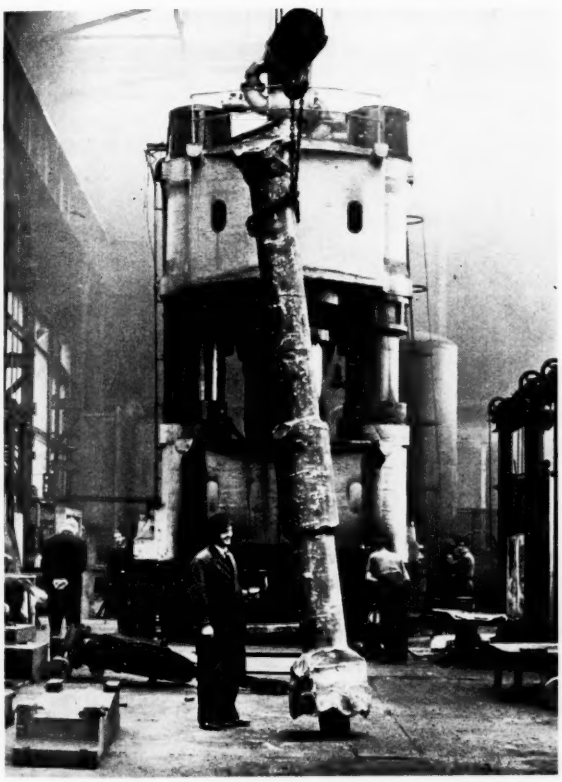

FIGURE 1. A forging weighing approximately 3,000 lb.

TABLE I

Specification

	L 65	D.T.D. 683
0·1% P.S.	26	27
U.T.S.	30	32
EL%	8	7
Solution Treatment	505 ± 5°C.	465 ± 5°C.
Precipitation Treatment	160 – 190°C.	110 – 140°C.

Composition

		L 65	D.T.D. 683
Major	Copper	3·8 – 4·8	0 – 1·5
	Magnesium	0·55 – 0·85	2·0 – 3·5
	Silicon	0·6 – 0·9	–
	Zinc	–	4·5 – 6·5
Minor	Manganese	0·4 – 1·2	0·25 – 1·0
	Chromium	(0 – 0·3)	0 – 0.5
	Titanium	0 – 0·3	0 – 0·3
Imps.	Iron	1·0 Max.	0·5 Max.
	Silicon	–	0·5 Max.
	Nickel	0·2 Max.	–
	Zinc	0·2 Max.	–

(*iii*) low level of internal stress. The inevitability of residual stress in any heat-treated component has often been ignored by the designer although painfully obvious to the production engineer because of distortion in machining. To achieve a low stress level may involve troublesome machining schedules and the acceptance by the designer of the slightly lower strength level given by quenching in hot water.

These factors are discussed at greater length in later sections of the paper.

3. Alloys for use in Large Forgings

The choice of alloy is very narrow and in fact is limited to two types by the inescapable requirement of high strength. These are the aluminium-copper-magnesium-silicon alloys of B.S.S.L65 and the aluminium-copper-magnesium-zinc alloys of D.T.D.683, and the compositional and mechanical property requirements of these specifications are set out in Table I.

Both these alloys are heat treatable, the desired properties being obtained in the finished forging by a solution treatment followed by a precipitation treatment, the details of which are also given in Table I. In the first high temperature treatment, the main alloying elements are dissolved in the aluminium matrix

and are retained in solution for a short period by quenching the material in water. In this condition the alloys are relatively soft and the final high strength is developed by a second treatment, at a much lower temperature than the first, which allows the dissolved elements to arrange themselves into definite intermetallic compounds; these separate from the aluminium matrix as minute particles generally invisible in the ordinary microscope although readily seen at high powers in the electron microscope. A somewhat similar but less intense hardening takes place on allowing the quenched material to stand at room temperature.

Copper, magnesium and silicon take part in the hardening of the L65 type and copper, magnesium and zinc in the D.T.D.683 type. Of the other elements present, manganese plays an essential part in developing high strength as will be discussed later, and chromium has a similar kind of effect; titanium helps in refining the cast structure; while the remaining elements (iron and zinc in L65, iron and silicon in D.T.D.683) must be regarded as unnecessary but economically unavoidable impurities.

A full appreciation of the factors determining the quality of a large forging is impossible without some consideration of the microstructure of the alloys used. The as-cast structure of D.T.D.683 shown in Fig. 2 is typical. The individual crystals of aluminium formed during freezing contain some of the hardening elements in solid solution but most of the alloying elements are present as a complex network of intermetallic compounds surrounding, and largely separating, the crystals. These compounds, which play a direct part in hardening, dissolve on heating to a temperature near that recommended for solution treatment and, in fact, dissolve fairly readily in pre-heating for hot working (Fig. 3). They are not a feature of the heat-treated structure but can be seen as widely dispersed minute particles in annealed or as-forged material. The hardening compounds in L65 dissolve less readily on heating and some residue will often be found even after prolonged solution treatment. The elements not playing a direct part in hardening mainly exist as intermetallic compounds which do not dissolve on heating. These compounds form an embrittling network which can be troublesome in hot working and which must be adequately broken up by the general deformation if high ductility is to be achieved in the finished forging.

A third important feature of the as-cast structure is the non-uniformity of composition within each individual crystal of the aluminium matrix; in D.T.D.683 these crystals tend to be zinc-rich at the core and copper-rich at the periphery and this can be brought out by suitable etching (Fig. 2). Compositional differences in L65 are not so easily demonstrated but undoubtedly exist. In both these alloys a small amount of manganese (or chromium) in solution as-cast subsequently separates as a visible precipitate within the individual crystals and has a marked effect on recrystallisation and directionality.

It is worth while to make some comparison of the general properties of the two materials. B.S.S.L65 is the ultimate development of the old-established Duralumin type of alloy and its basic characteristics are well known; it established itself as an aircraft material during the early years of the 1939-45 War. Its natural ageing properties are similar to the old alloy B.S.S.L1, reaching 15 tons/in.^{2} P.S., 25 tons U.T.S., 15 per cent. elongation in 3-5 days and remaining substantially constant thereafter; considerable rectification of distortion can be safely carried out in this condition. It has two main drawbacks. To achieve maximum strength when the material is subsequently subjected to precipitation treatment, the solution treatment temperature must be taken within a few degrees of the temperature at which traces of liquid appear in the alloy, and quench cracking, blistering or other overheating troubles may arise if such treatment is not very carefully controlled. In extruded form it shows a marked tendency to develop an annulus of coarse grain in solution treatment and care is sometimes needed to prevent coarse grain in certain parts of a forging.

D.T.D.683 is an alloy of more recent development, and in fact its composition is not yet rigorously stabilised for any one of its constituent elements. In comparison with L65 it suffers from the absence of a continuous development from an established and simpler material, since (with D.T.D.363) it appeared almost fully fledged as the highest strength alloy available. If precipitation treatment is not carried out after quenching, natural ageing continues for an indefinite period and strengths are ultimately reached comparable with those obtained after full heat treatment although with lower values of proof stress. If rectification after quenching is delayed there is risk of cracking and a high level of residual stress. In our experience the material is not prone to coarse recrystallisation in extrusions and does not give trouble in forgings; neither is it susceptible to overheating troubles, the temperature of incipient fusion being well in excess of

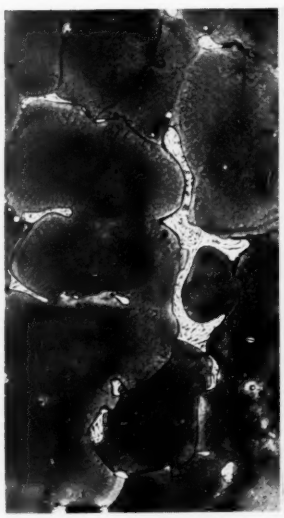

FIGURE 2. The as-cast structure of D.T.D.683.

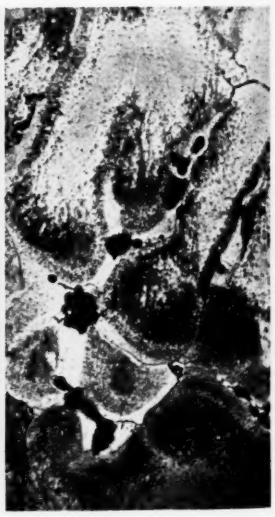

FIGURE 3. Structure of D.T.D. 683 in the pre-heated condition.

the solution treatment temperature, even in only moderately wrought samples. Its corrosion resistance is nominally good although failures attributed to stress corrosion have occurred. The tendency to intercrystalline attack is much greater in the naturally aged than in the artificially aged condition, in direct contrast to the behaviour of L65. In spite of the statements of Dix, that the presence of chromium prevents stress corrosion in this type of alloy, there is considerable divergence of opinion on the significance of this factor and in forgings, at any rate, the adverse effect of chromium on the tensile properties attainable in hot water quenching makes its addition a debatable benefit.

4. Forging Stock

Small or medium sized forgings may be made from extruded bar or sometimes from rolled plate since these products are readily available and advantage can be taken of the extensive working that these forms have already undergone, except when their directionality of structure is an embarrassment. With the size of extrusion press available in this country, however, extruded bars above 10 in. in diameter may not be sufficiently worked to justify their use and large forgings must be made by direct manipulation of cast stock. A similar position exists with plate stock above about 3 in. thick.

Today's "large forging" may weigh anything from 30 to 3,000 lb. before machining and a casting some 50 per cent. heavier than this is needed to provide the stock. The demands on the foundry are very exacting and wide experience, with rigorous control of every detail of the casting process, is necessary if the forging is to be of the desired quality or, for that matter, if it is to be made at all. The billet finally sent to the forge is commonly up to 20 in. diameter or of a polygonal section of equivalent area. It must be sound, fine grained and free from cracks, oxide inclusions or significant micro porosity. The surface must be machined to remove irregularities, blebs, laps, and so on, and the internal stresses due to casting must have been eliminated. These requirements are particularly onerous in the case of D.T.D.683, whose casting is generally acknowledged as the most difficult technically and unrewarding economically of all the aluminium alloys.

The necessary quality of stock can only be obtained by a casting method using direct water cooling of the billet such as the semi-continuous method established in this country and based on the Alcoa "Direct -Chill" process. The casting of billets up to 16 in. diameter is fairly generally practised but larger sizes demand a more specialised technique and critical control. As far as is known to the authors, the largest billets used for production forging in this country are 26 in. as-forged octagons, 10 ft. long and weighing 2 tons 15 cwt., the first of which was produced in 1947. One of these is illustrated in Fig. 4.

In considering the casting of stock for large forgings the following detailed problems must be satisfactorily overcome:—

(*i*) the melt must be accurately controlled in composition, carefully fluxed to eliminate oxide inclusions, and the grain refining additions must be made.

(*ii*) it must be rigorously degassed by a stream of bubbles of chlorine gas and strict precautions taken to prevent subsequent pick up of gas.

(*iii*) the metal must be poured into the mould at a carefully controlled temperature and in a

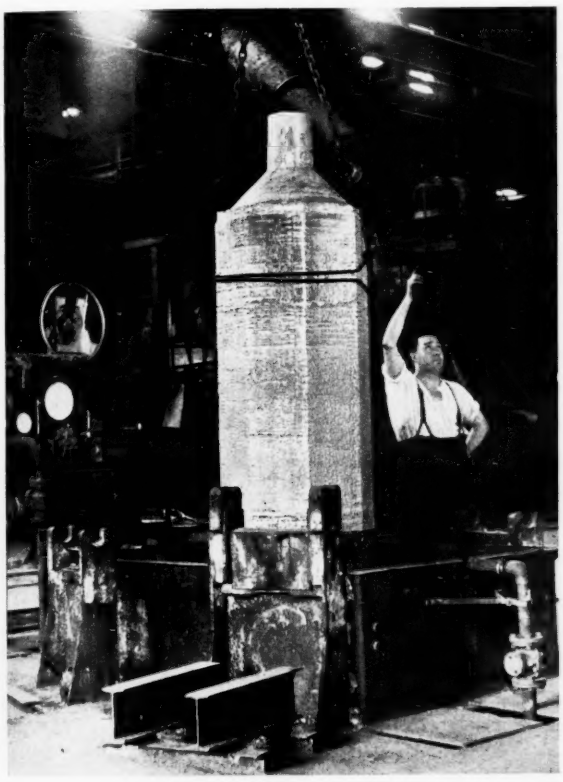

FIGURE 4. One of the largest billets used for production forging.

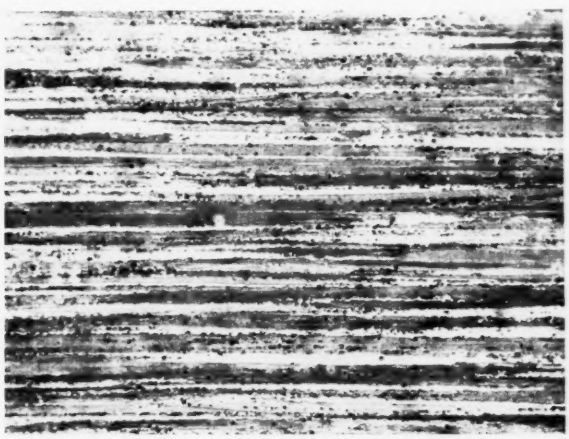

FIGURE 5. The longitudinal structure of an extruded bar.

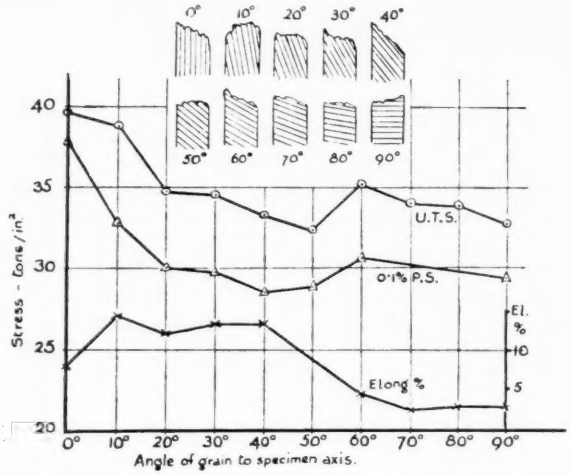

FIGURE 6. The mechanical properties of test pieces.

manner minimising the risk of turbulence and oxide entrapment.

(*iv*) the rate of casting and the amount and distribution of the cooling water must be controlled to give the maximum rate of freezing without causing cracking due to shrinkage stresses and with due regard to the direction of heat extraction so as to ensure a billet as free as possible from micro-porosity.

All billets are carefully examined with supersonic flaw detecting apparatus. In addition, all billets for difficult forgings and a proportion of other billets are examined for the level of micro-porosity by chromic acid anodising of a heat-treated slice of the cast material.

5. The Effects of Forging on Cast Stock

It has already been pointed out that no forging can be completely free from directionality. The casting, which is the raw material of the forging, is in general non-directional in mechanical strength and ductility. It has, however, a cellular pattern of grain shape and insoluble compound, and working which produces an external shape markedly different from that of the casting will tend to produce a similar distortion of the elements of its structure. In the aluminium-zinc-magnesium alloys in particular, the cellular structure of the cast material is remarkably persistent, and can be recognised in the wrought material even after drastic deformation and heat treatment have caused recrystallisation, so that the existing grain boundaries in the wrought and heat-treated component have no relation to the original cast grains, whose boundaries are apparent as "ghosts" running through the structure.

Directionality in structure implies some directionality in properties. Take, for example, an extruded bar, the longitudinal structure of which is shown in Fig. 5. It will be seen to be highly directional. Fig. 6 sets out the mechanical properties of test pieces with axes in various directions in the bar.

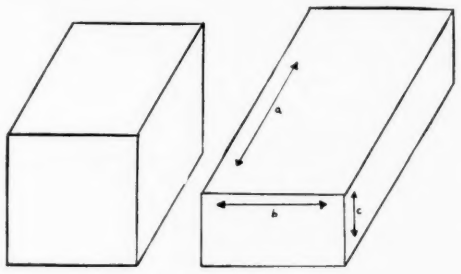

FIGURE 7.

In a forging there are three significant directions which have to be recognised in respect of mechanical properties. In a forged block these may be defined as "longitudinal," "long transverse" and "short transverse" respectively, and are illustrated in Fig. 7 as *a*, *b* and *c* respectively.

These directions are apparent in practically all forgings, *c* having the poorest properties, and *a* the most satisfactory. The reasons for these variations in mechanical properties may be stated to be:—

(*a*) If the alloy has not recrystallised the variations may be due to the development of the fibrous crystal pattern with a strongly developed texture.

(*b*) If recrystallisation has occurred in heat-treatment there is likely to be a preferred orientation of the recrystallised grains.

(*c*) The insoluble compounds (which have been illustrated) exert an effect similar to that of slag in wrought iron.

(*d*) The persistence of the cellular structure of the original cast stock will give alternating layers of stronger and weaker fibres in the material.

(*e*) The general effect of any minor inclusions such as films of oxide which exert little effect when randomly located but add their contribution to the whole effect when aligned in definite planes normal to the direction of stress.

Not all these factors will operate in all cases, and the severity of their influence will depend to a great extent on the alloy under consideration, the shape and size of the forging, and of course, the method of producing the forging. Enough has been said, however, to make it clear that there is a limit to what can be achieved in the way of isotropic properties in a forged high-strength aluminium alloy, and to indicate how essential it is for the designer of the forging to discuss his problems with the maker as early as possible in the design stage.

6. Other Kinds of Forging Stock

In addition to the use of cast stock, it is sometimes convenient to use either extruded, or rolled stock. This applies particularly when strength is required in preferred directions, and less importance is attached to strength in directions other than these. A case which comes to mind is the production of forgings in which a very much higher strength properly disposed can be made available by the use of extruded stock (Fig. 8).

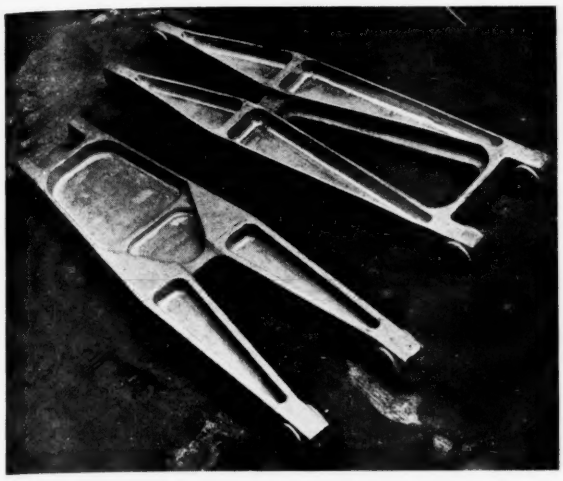

FIGURE 8.

Similarly, the production of flat plate-like forgings is facilitated by the use of rolled plate stock, in which, by suitable hot working techniques, mechanical properties of a satisfactory level are obtained in directions longitudinal and transverse to the direction of rolling, and satisfactory properties in the short transverse direction, if required, are achieved locally by suitable forging techniques.

7. Methods of Forging

The internal structure of a forging can be profoundly affected by the method of production. In the smaller class of product which is produced by the time-honoured methods of drop-forging it is possible to distribute the work more homogeneously through the mass of metal because the nature and scale of the drop-forging process is such that the surfaces of the forging and of the tools which shape it may be adequately lubricated. In addition, with a sharp blow such as is imparted in hammer forging or in a drop-stamp, there are inertia effects which tend to work the metal more thoroughly near to the surface of impact.

In press-forging between flat tools friction between tool and metal restricts sideways spread and, in effect, the metal in contact with the tool acts as part of the tool itself and transmits pressure through the mass being forged, without itself suffering deformation. This effect is illustrated in Fig. 9. As the thickness of the piece being forged is reduced, it will be seen that the central plane becomes increasingly worked due to the near approach together of the dead metal cones in contact with the tools. Thus it is possible, if forging in this direction is carried too far, to obtain a forged piece having two outer layers only lightly worked, with little dispersion of the cast structure and in between them a heavily worked, highly directional core, having a strongly developed fibre structure, but having also poor ductility in a short transverse direction.

It is clear that this is not the way to produce forgings of good quality, but it is important to realise that

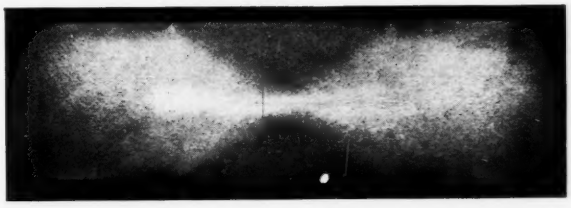

FIGURE 9.

in press-forging very large masses of metal the effect of work may in some cases be non-uniformly distributed, with consequent difficulty in achieving, in particular, high ductility in certain locations. Such locations may be in areas where there are drastic changes of section, and at flash-lines in die-forgings.

There are various ways in which these features may be overcome : the use of a hammer, for instance, where practicable, the use in presses of tools of small area and of special contours, the selection of forging schedules of the right type, and the controlling of friction in dies by maintaining them in well-polished condition and by the intelligent use of suitable lubricants.

There will always remain, in die forging, the difficult problem of the flash line, for to fill a die, flow from the edges must be hindered by the decreasing aperture between the dies as they come closer together. This produces, outside the dies, an extruded "flash" of gradually decreasing thickness. The metal comprising this "flash" comes from within the block, and not from near the surface, so that an area of intense local work arises (Fig. 10). This condition does not arise in the simpler types of forging where the pre-forged use fits the die very nearly, and the amount of flow is not great, but where thin flanges are made, and where a U-channel is involved, this intensely local effect is difficult to avoid. It will be seen that flash-line areas are extreme examples of the short-transverse test referred to in the section on the forging of cast stock, and are in consequence likely to show low ductility.

8. Types of Forgings

The steps in the production of a forged block from which components may be machined are seen, therefore, to consist in working the material adequately and homogenously to provide a block having no strongly preferred orientation, nor any intensely locally worked areas. It is not advisable that such blocks should be heat-treated before machining, as stresses are likely to develop which may give rise to failure in service. In such cases the block should be machined in the "as forged" condition nearly to the finished size, heat-treated, allowed to rest for about 14 days (or alternatively submitted to precipitation treatment) and then finally machined to its finished dimensions. Such a product cannot be regarded as entirely a satisfactory one, but for prototypes, or for the occasional emergency, it may prove to be the only solution.

Where it is desirable that the fibre of the finished part shall conform more reasonably to its shape an open

forging may be satisfactory. In this case it is generally possible to produce a shape which approximates sufficiently near to the finished shape that, when machined, its strength is adequate. This practice is not usually possible in cases where forgings have excrescences, such as lugs, which have to take direct loads; it is only feasible when the general load is distributed. It is usually necessary, in such cases, to machine the rough forgings all over, and again it would be preferable to take the forging in the "as forged" condition, rough machine it, and heat treat prior to final machining to size.

Where it is desired to achieve maximum structural efficiency and to perform the minimum of machining a die forging is essential. The requirement for a die forging arises when a design has been stabilised and when quantity production is envisaged.

It is now becoming common practice to regard a die forging as a means of obtaining a component to tolerances sufficiently close to permit putting it into service without machining, except in those places where it has to fit another part of the structure. In these cases the user wishes to be sure that there is no surface blemish whatever and, in effect, the problem of all-over machining has been passed back from the user of the forging to its maker, who has virtually to machine the product all over before the final pressing to size in the dies. In this case the grain flow follows accurately the contours of the forging, but the cost of production is greatly increased owing to the need for meticulous care in surface preparation, and for the very close control of dimensional tolerance which is demanded, not only in forging, but in heat treatment. The preparation of a "use" for die forging is similar to that involved in open forging, although where shapes are very complicated two sets of dies may be needed, one for producing a preliminary shape, and a second for completing the final shape without producing undue local directionality, which can arise if too much deformation is left until the final pressing to shape.

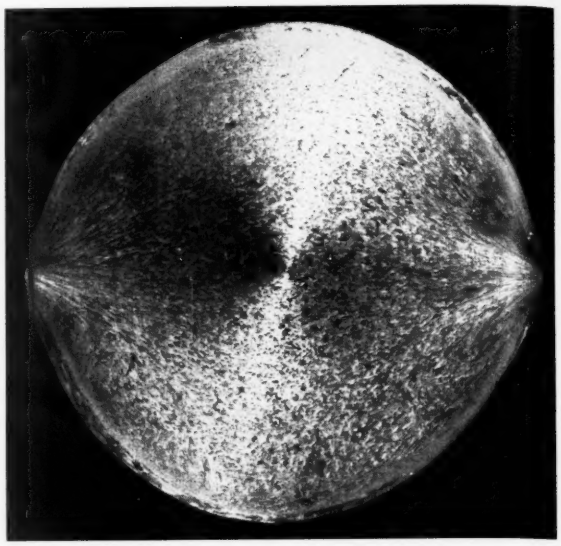

FIGURE 10.

9. Heat Treatment

9.1. EFFECT ON MECHANICAL PROPERTIES

Practically all forgings are subjected to both solution and precipitation heat treatment, and the general effect of these treatments is similar. In the case of the alloy conforming with L65, room temperature ageing occurs after quenching from 505°C and strength

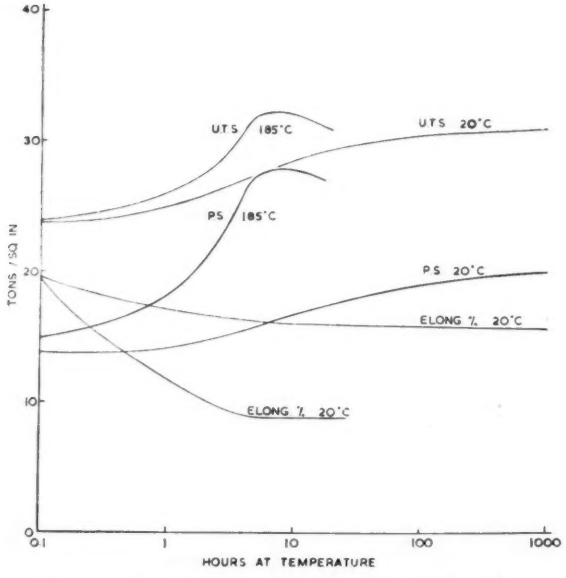

FIGURE 11. Precipitation hardening of L65 material.

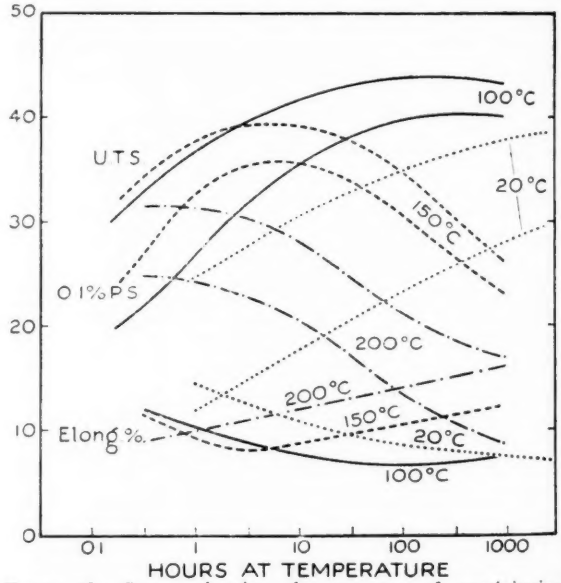

FIGURE 12. Curves showing the progress of precipitation hardening of Duralumin K at various temperatures after quenching from 460°C.

increases for about 5 days, after which a reasonably stable condition is reached. The alloy D.T.D.683 after quenching from 460°C ages at room temperature with a rapid increase in strength in the first few days, but unlike the other alloy it continues to age for a very considerable period, ultimately achieving properties approaching those of the fully precipitated alloy.

To achieve maximum strength both alloys may be subjected to low temperature heat treatment subsequent to solution treatment. This is known as precipitation treatment and is done at 165 to 185°C for L65 alloy, and at 130 to 140° with D.T.D.683. The periods necessary vary according to the temperature used and in forgings may vary between 8 to 24 hours. Figs. 11 and 12 show the effects of room temperature ageing and precipitation treatment on the mechanical properties of L65 and D.T.D.683 respectively.

9.2. EFFECT ON RESIDUAL STRESSES

The properties shown in Figs. 11 and 12 apply to forged test pieces quenched in cold water. It will be appreciated that if a large forging of complicated shape is quenched in cold water, strains are induced which might result in marked distortion on machining; indeed in some cases where there are abrupt changes in cross section actual cracking might arise. In general the level of internal stress in a component is related to the speed of cooling, and this, in its turn, to the temperature and nature of the cooling medium.

It was satisfactory in earlier days to minimise distortion by quenching in oil, but modern practice is to use water as the quenching medium, and to control its temperature. Fig. 13 shows the effect of quenching a standard cylinder from 500°C in water at various temperatures, and it will be seen what wide variations in cooling rate may be achieved and that the temperature of the water becomes significant above about 70°C. This effect is shown in Fig. 14, which shows the level of stress induced in a D.T.D.683 extruded tube wall quenched at 70°C and at 85°C.

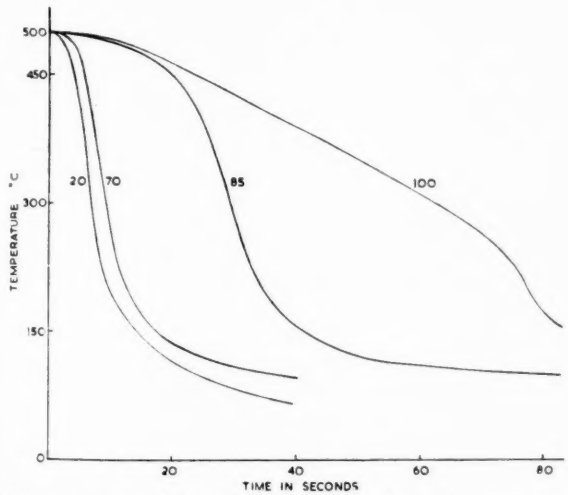

FIGURE 13. Quenching of a standard cylinder in water at different temperatures.

9.3. OTHER EFFECTS

It is quite usual today to quench forgings in water at 85°C, and, with large forgings in particular, this may have some effect on the level of mechanical properties achieved. Fig. 15 illustrates the double effect of the temperature of the quenching medium and the mass of the specimen on the properties of D.T.D.683 bar.

A brief reference has been made earlier to the effect of Chromium on D.T.D.683. Where it is necessary to quench a forging in hot water, and in particular where the forging is of large mass, note should be taken of the marked effect of Chromium in diminishing properties when the rate of cooling is slow. Fig. 16 shows this effect on samples of D.T.D.683 extruded bars (containing various amounts of chromium) quenched in boiling water.

10. Resistance to Corrosion

The authors feel that it is hardly apposite to discuss in any detail in a paper on the production of large forgings, the vexed question of resistance to corrosion, but feel that unless some reference is made to the matter there may well be an unnecessarily prolonged discussion.

A great deal of nonsense has been written and spoken about the corrosion resistance of the strong alloys. On the one hand it has been suggested that aluminium alloys are generally superior to other materials, derogatory comments being made about the rusting of steel; on the other hand it has repeatedly been suggested that these alloys are completely unstable and liable to disintegration. Neither of these statements is true, but it is certainly true that it is necessary to

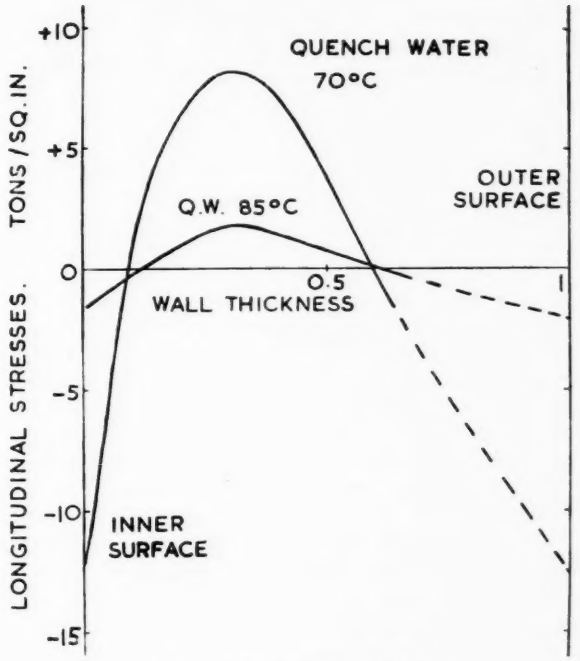

FIGURE 14. D.T.D. 683 tubes.

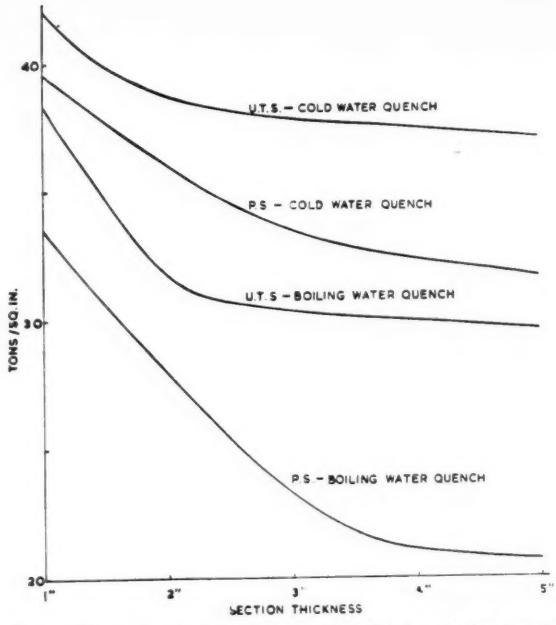

FIGURE 15. Core tensile tests. D.T.D.683 bar (0·05% C.R.).

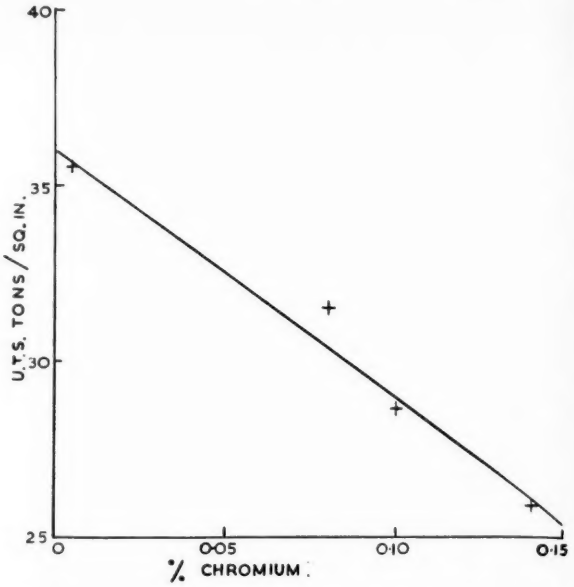

FIGURE 16. Effect of chromium on the core U.T.S. of 3 in. thick D.T.D. 683 extrusions quenched in boiling water.

take precautions against the effects of atmospheric corrosion in highly stressed strong alloy components in aircraft. In spite of the apprehension which is continually being voiced about the stress corrosion resistance of the modern high strength alloy, experiments made in the laboratory suggest that their resistance to stress corrosion is not low, but that under certain conditions failures of a rapid nature may arise. Much has been written on this subject and those who are interested should read the Campbell Memorial Lecture by E. H. Dix Jnr. given recently to the American Society for Metals. Care should be taken in studying Dix's conclusions, which are that the new materials are no more prone to fail by stress corrosion than the older ones, conditions being similar.

The authors of the present paper suggest that these conclusions of Dix are correct, that in themselves these alloys are not fundamentally worse than the earlier types of alloy, but that the conditions under which they are being used—conditions which arise because of the need for stronger, lighter aeroplanes, and as suggested earlier, because of the requirement of higher elastic strength (which unfortunately means a narrower plastic range in the new alloys)—make for a markedly greater effect of any departures from normality in service, such as the presence of stress raisers, stresses which are built into the structure, or quite minor corrosion effects.

It may well be that the addition to the alloys of certain elements may so modify their behaviour as to improve their susceptibility to intercrystalline attack. With ever decreasing factors of safety there is a need for greater foreknowledge in the shops of the aircraft constructor, on the part of his assemblers, and of those who have to maintain the aircraft to avoid any incidental damage, any unforeseen stress, any condition which will promote corrosion; because the effects of these factors on the components may well create conditions where the local stresses to be borne are so high as to result in rapid and inevitable failure. This may be particularly true, for example, with corrosive attack if the notch or pit which is formed is so located as to exert its ill-effect in directions where the fibre of the material is least satisfactorily disposed to withstand it. Emphasis is laid down strongly here because the authors have a feeling that so often the alloy itself is regarded as the cause of a failure, when often some simple precaution might have prevented failure.

The ultimate solution of these problems lies, in part, in the hands of the metallurgist, but in equal part the engineer has his responsibility. There is no alloy which has all the virtues; the price of greater efficiency is greater care. An attempt has been made in this paper to convey to its readers a realistic picture of the nature of these alloys in terms which it is hoped are intelligible, because of this conviction that greater knowledge of their characteristics will lead to a more advantageous usage of these interesting products.

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Clear Air Turbulence and Civil Jet Operations

by

E. CHAMBERS, M.B.E., M.A.

(*British Overseas Airways Corporation*)

1. Introduction

How much is known about high altitude clear air turbulence? Sufficient to show that aircraft may, with little or no warning, experience bumpiness which the pilot would describe as "moderate" or, on occasions, "severe," at altitudes up to at least 40,000 feet, thus including altitude bands where commercial jet aircraft will be flying during the next few years. The phenomenon, therefore, is of significance to airline operators and the requirement is for the aircraft commander to be supplied with sufficient information to enable him to avoid such turbulence, or to provide him with adequate warning so that crew and passengers can be properly prepared for it. This does not imply that there is evidence to suppose that clear air turbulence may be of such severity as to affect the safety of a flight. It is important, however, to take good care of the passengers and their comfort is an essential consideration. Thus, even slight "cobblestone" turbulence is of significance in a Comet flight in that it disturbs the characteristic smoothness of such flights. "Moderate" bumps might prove most disconcerting during the service of meals, or drinks, while bumps of greater severity may result in physical discomfort and necessitate the fastening of seat belts.

The turbulence is usually of the "cobblestone" type, so named from its effect of producing short, sharp, up and down movements without resultant change in altitude. The effect may be likened to that of a speedboat travelling through a choppy sea. In extreme cases, a sudden and unexpected severe bump might occur and may be compared with the bumps sometimes experienced when flying through cumulonimbus cloud. On only rare occasions has wing dropping been reported in severe turbulence, which indicates that the eddies usually are of larger dimensions than the wing span of existing types of aircraft.

2. Review of Recent Investigations

How far can the requirement of the aircraft commander be met? The following brief summary of clear air turbulence research indicates that considerable progress has been made in associating the frequency of occurrence of severe turbulence with certain types of weather situation, particularly jet streams but, on the other hand, the results are by no means conclusive and no satisfactory theory has been developed to explain the cause of clear air gusts. Bannon[1] analysed 92 cases of severe turbulence reported over the British Isles at heights above 20,000 ft. during the period 1946 to July 1951 and found that 67 per cent. occurred in the vicinity of jet streams. Of these, 75 per cent. occurred on the low pressure side of the jet stream and there were only three cases reported in the zone below the level of the jet axis and on the high pressure (warm air) side of the axis. Most of the other cases were associated with upper lows or troughs or strong winds not identifiable as jet streams. About 7 per cent. were "unclassified," *i.e.* they were not associated with any particular upper air pattern. Jones[2] extended this analysis and examined a further 147 cases of severe clear air turbulence reported over or near the British Isles during the period August 1951 to February 1953 at altitudes ranging from 15,000 ft. to 48,000 ft. Of these, 71 per cent. were in the vicinity of jet streams, 9 per cent. were "unclassified" and practically all the rest were associated with upper lows or troughs or strong winds, thus confirming the results found by Bannon. Of the cases reported near jet streams, 75 per cent. occurred on the low pressure side of the axis and less than 10 per cent. in the quadrant below and on the high pressure side, again confirming Bannon's findings. Two cases of exceptional severity were reported below and on the low pressure side of the axis of well defined northwesterly jet streams in which the maximum wind speeds were of the order of 155 and 170 knots respectively.

The main conclusions reached were that moderate or severe clear air turbulence may be expected in regions where either or both of the following conditions are satisfied:—

(*a*) Marked changes of wind in the vertical (vertical shear).

(*b*) Marked change of wind in the horizontal or over an isentropic surface (horizontal or isentropic shear), say, greater than 35 knots per 100 nautical miles.

A more recent case [3] of a Canberra aircraft which overturned at 40,000 ft. during a right hand turn, occurred above the axis of a northwesterly jet stream (maximum wind speed approximately 120 knots) on the warm side 250 miles from the axis and about 2,000 ft. below the tropopause. The incident occurred in an area of pronounced vertical and horizontal wind shear and there were several reports of standing waves in the air stream.

The U.S. Weather Bureau and the N.A.C.A. have analysed two years' records of pilots' reports of high altitude turbulence[4] and again there is evidence that severe turbulence is usually associated with zones of marked wind shear in the vicinity of jet streams. It was also noted that the worst turbulence is often found in

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the portion of the jet stream where the wind speed along its axis is a maximum. This often corresponds with a zone of maximum wind shear. In analysing reports of severe turbulence, Jones[5], however, did not reach any conclusive result concerning the variation of turbulence along the axis of jet streams, although the evidence suggested that turbulence was more severe near the exit than near the entrance to the jet streams. This point will be considered again in Section 5.

The association of severe turbulence with jet streams led to special investigational flights to explore the atmosphere in and near jet streams and to make observations of the turbulence experienced. Thus the Aero Flight of the Royal Aircraft Establishment, South Farnborough[5], investigated seven jet streams from April to December 1951. The worst turbulence encountered was "moderate" on one occasion and "perceptible" on six occasions. In three cases the aircraft was flown in areas associated with very high values of both horizontal and vertical wind shear but turbulence was only "perceptible."

In operation "Upper Bumps"[5], the Royal Air Force investigated 23 jet streams during the period March 1952 to February 1953. The worst turbulence encountered was "severe" on nine occasions, "moderate" on nine occasions, "perceptible" on three occasions and "nil" on two occasions.

Mosquito aircraft of the Meteorological Research Flight[6] made 20 special flights during the period May 1951 to August 1952 to investigate atmospheric structure near jet streams and accelerometer readings were taken at one minute intervals. The maximum acceleration recorded was 0·4*g* (most pilots would report this as "moderate") and this was an isolated bump which occurred 8,000 ft. below and 50/100 n.m. on the low pressure side of the jet stream axis. No bumps exceeding 0.2*g* were found in the quadrant below the axis on the high pressure side; slight bumps, less than 0·2*g*, occurred on 33 per cent. of the time and moderate bumps on less than 5 per cent. of the time.

During the British European Airways Clear Air Turbulence Project[7], severe turbulence was encountered in two jet streams, but on more than 20 other occasions, flying across or near jet streams produced "nil" turbulence. The most severe case was in crossing a southwest jet stream near Stoke-on-Trent, although 30 minutes earlier the aircraft had traversed the jet stream in a reciprocal direction in smooth air.

Mosquito aircraft of No. 540 Squadron Royal Air Force[8, 9] traversed two jet streams (axis 340° on 18th January 1952 and 260° on 1st September 1952) at constant altitude (30,000 ft. which was approximately the altitude of the axis of the jet stream in both cases), speed and course for the purpose of measuring winds at short space intervals from photographs taken at every 12 to 15 seconds. In spite of very high values of horizontal wind shear along parts of the flight path, particularly on the "cold" side of the jet, however, no turbulence was experienced except "cobblestones" near the tropopause on 1st September 1952 over North Scotland some 150 miles north of the jet axis, where winds were light with only small values of horizontal and vertical shear. Maximum wind speeds as found by the aircraft at the axis of the jet streams were 170 knots and 112 knots respectively.

During the winter of 1952/1953, jet streams over the eastern United States were explored by two fighter aircraft of the United States Navy which were based at Patuxent, Maryland. Missions were assigned to these aircraft by Project "AROWA" of the United States Bureau of Aeronautics and the following statement appears in the Final Report[10] of the results obtained: "Most important to us appears the result that several strong jets were virtually without turbulence, in spite of intense lateral wind shear and that the record as a whole indicated only weak turbulence areas."

Thus, the exploration of jet streams has shown the irregular and patchy nature of turbulence in areas thought to be favourable for the most severe form of the phenomenon.

It might be of significance also that there have been frequent reports by aircraft, including B.O.A.C. Comets, of slight to moderate turbulence, and isolated reports of severe turbulence, at or just above the tropopause in situations where there has been no evidence of high values of wind shear.

Following a flight in a Canberra aircraft from England to Australia, the pilot, Wing Commander Cuming, R.A.A.F., reported[11] "Turbulence was always noticed on the climb when passing through inversions and when passing through the tropopause. There was more turbulence, generally speaking, when going through the tropopause than through inversions."

By computing vertical shear and Richardson number near and just above the tropopause from wind observations made at Larkhill, Bannon[12] showed that the values were of the same order as those obtained at similar heights when away from the tropopause. There are, therefore, no "special" values of vertical shear localised at the tropopause. Bannon concluded that horizontal shear might be an important factor in tropopause turbulence and likewise in turbulence found in thermally stable layers in the troposphere *e.g.* at "dry" fronts. He further pointed out that it is difficult to understand how turbulence can persist in such thermally stable layers unless the eddies are horizontal.

This type of turbulence was reported on several occasions during the B.E.A. Project[7] and acceleration increments of 0·2*g* to 0·4*g* were recorded. It was usually associated with an upper low, or trough, although with no abnormal values of wind shear.

Murray[6] reports that a Mosquito aircraft of the Meteorological Research Flight encountered a bump of 0·25*g* near the tropopause where the horizontal shear and the vertical shear were apparently quite weak.

During a Comet flight to the West of Ireland on 17th December 1953, "moderate" clear air bumps were experienced near the tropopause and post-flight examination of the available meteorological data gave no evidence of strong wind shear, the Richardson number being estimated at about 20 and horizontal shear at about 0·03 hours^{-1}. It would appear, therefore, that

pronounced wind shear is not a necessary condition for the occurrence of clear air turbulence.

It has been suggested also by various authors that clear air turbulence may be associated with gravity waves, or in some cases, with standing waves such as may occur on the lee side of mountain ranges. Fjoertoft[13] has shown that in two-dimensional motion of a barotropic atmosphere, instability waves will occur at a turning point in the velocity profile of the westerly winds of middle latitudes, *e.g.* jet stream axis, provided that the wind shear exceeds a certain critical value depending on the latitude. No satisfactory dynamical theory has been put forward, however, to account for any subsequent turbulent motion and it is not clear as to how the waves would degenerate into turbulence. Nevertheless, the characteristics of "cobblestone" turbulence, with its regular eddies, suggest the association of some sort of wave-like motion, although part of the effect may result from the "response" characteristics of the aircraft.

There must be conditions in which certain types of smooth flow degenerate into turbulent motion by local effects or by "trigger" action. Radok[14] suggested that topography was an important factor in the occurrence of localised severe turbulence experienced by a Canberra aircraft in a jet stream at 30,000 ft. near Melbourne in August 1951. It is known that mountain ranges may cause deformation of the air flow up to heights of 40,000 ft. or more and the above incident occurred when the aircraft reached a gap in the Australian Alps.

No doubt clear air turbulence may result from a variety of causes and the fact that it is often highly localised means that it is undetected on many occasions and any statistical analysis available at the present time must necessarily be based on a relatively small sample. It should be borne in mind also that turbulence as reported by aircraft provides information on only a portion of the total gust spectrum, since eddies which manifest themselves as "bumps" must be of certain limited dimensions, say 50-500 ft. in diameter.

The main deficiency in our understanding of the problem is the absence of a comprehensive dynamical theory to explain the mechanical structure of the turbulence.

3. Severity

From April 1948 to January 1950, a Research Project to investigate clear air turbulence was undertaken by B.E.A.[7] and supported by the Ministry of Supply. Mosquito aircraft, fitted with recording accelerometers, flew vertical "sawtooth" tracks between approximately 15,000 ft. and 35,000 ft. over various routes in Europe for the purpose of locating turbulent areas. On encountering bumps greater than $0{\cdot}2g$, the area was "searched" in order to provide information on the horizontal and vertical extent of the turbulence, temperature gradients, and so on. In over 92,000 miles flying, bumps of $0{\cdot}5g$ or more were encountered on only three occasions, the maximum ($0{\cdot}7g$ with an equivalent gust velocity of 26 feet per second) over Stoke-on-Trent near a jet stream. All the severe cases occurred in the "middle" (approximately 20-25,000 ft.) altitude bracket.

With the object of obtaining some factual data on high altitude turbulence over Comet routes, a Swiss Peravia self-recording accelerometer used in the B.E.A. Project[7] was obtained on loan from B.E.A. and fitted to the Comet I prototype "Zebra King" which was used for the early B.O.A.C. development flights. However, these flights did not encounter any noteworthy clear air turbulence and it soon became apparent that turbulence in cumulonimbus cloud even at cruising altitudes was likely to be much more significant. By arrangement with the Royal Aircraft Establishment, Farnborough, a compound counting accelerometer* also was fitted to "ZK" and this type of accelerometer later was installed at various times in three Comet I aircraft operating scheduled services to South Africa and the Far East and some 2,000 hours flying were logged. There were only seven cases (including two on one flight) of bumps equal to, or greater than, $\pm 1g$ but none of these was in clear air. Further details of these gusts and also of the gusts recorded in clear air are given in Table VI. It will be seen that the maximum bump (g recording) in clear air was $-0{\cdot}6g$ at 39,000 ft. over the Alps and the maximum calculated gust speed was 20 feet per second (corresponding to $+0{\cdot}5g$) at 39,000 ft. just north of the Alps.

The pilots' subjective assessment of turbulence in Table VI*B* is more or less in line with the commonly accepted formula, *i.e.* "moderate" $\pm 0{\cdot}2g$ to $\pm 0{\cdot}5g$ and "severe" $\pm 0{\cdot}5g$ upwards. Captain D. F. Wilson of B.E.A. has stated[7], however, that during the B.E.A. Project, turbulence which was thought to have imposed acceleration increments of more than $1g$ appeared on the accelerometer trace in the order of $\pm 0{\cdot}6$ to $0{\cdot}7g$.

This experience at first sight contradicts qualitative reports of "moderate" turbulence by Comet pilots when increments of over $2g$ have been recorded on the Kollsman accelerometer mounted in the nose of the aircraft. However, these "g" readings do not give a reliable measurement of the accelerations imposed on the aircraft as a whole, since the instruments are installed well away from the c.g. Furthermore, "cobblestone" accelerations with a frequency near to that of the natural frequency of the accelerometer will be very much exaggerated by the instrument.

Hislop[7] estimated that the gust encountered by the Comet at 35,000 ft. over York on 14th November 1949 and described by the pilot, John Cunningham, as the worst he had ever encountered, was probably of the order of 35 feet per second and corresponded to an acceleration increment of about $1{\cdot}5g$, although increments of $+2g$ and $-2{\cdot}6g$ were noted on the accelerometer dial. Gusts of $1{\cdot}5g$ have been measured by Spitfires[12] in cumulonimbus cloud over the United Kingdom.

From experience of readings from Kollsman accelerometers mounted in Canberra aircraft, Hyde[15] estimated that clear air turbulence over the northwest of the

*Automatic observer photographs at 10-minute intervals the acceleration counts (in steps of $0{\cdot}1g$), air speed and pressure altitude.

British Isles in its severest form would give accelerometer readings of the order of $-1\frac{1}{2}g$ to $+5g$ (*i.e.* increments of $-2\frac{1}{2}g$ to $+4g$), but it is difficult to interpret these readings in relation to say, Comet aircraft, since aircraft characteristics must necessarily be taken into account. It was hoped to obtain some very useful information from test flying of Comet II aircraft from the Belfast base of Short Brothers & Harland but this programme, unfortunately, has been postponed.

It seems a great pity that so few of the reported cases of severe gusts in clear air have actually been recorded by accelerometers, since subjective reports of this type of turbulence are very difficult to assess. The rapidity (number encountered in unit time) of the bumps, for example, is an important factor. Nevertheless, the available evidence is that clear air gusts, in general, are less severe than gusts encountered in well developed cumulus and cumulonimbus clouds but, on occasions, gusts in clear air may be experienced, without any apparent warning, of an intensity comparable to the severe gusts sometimes encountered in cumulonimbus cloud over Europe. This lack of warning, of course, is of great significance to fast-flying aircraft.

4. B.O.A.C. Experience

Stratocruiser aircraft of B.O.A.C. frequently make use of jet streams when flying eastbound across the Atlantic and Captain B. C. Frost has stated[16] that "once in the jet stream, contrary to general belief, flying conditions usually are velvety smooth." It should be noted, however, that these aircraft almost invariably fly in the warm air well below the axis of the jet stream and this "quadrant" is recognised as being relatively immune from clear air turbulence.

Comet aircraft of B.O.A.C. have flown for a considerable number of hours in jet stream situations, including a number in the Japan area, where the strongest winds in the world, often associated with very strong wind shear, are to be found in the winter months.

With the delivery of production aircraft and the beginning of scheduled services, Comet captains were asked to report on turbulence experienced in flight over each sector operated and to file a "nil" report if none was encountered. Tables I to IV have been constructed from an analysis of all the reports obtained. Results from recording accelerometers carried in Comet aircraft have been discussed in the previous Section.

Of all the occasions when turbulence was experienced, the vast majority were reported as "slight" and less than 30 per cent. were of intensity "moderate" or greater. Less than 2 per cent. (9 cases) were reported greater than "moderate" and fuller details of these cases are given in Table IV. On one such flight (Karachi-Calcutta, 28th January 1953) when the tur-

NOTE:—Abbreviations (Tables I, II and III):

LON = London	LIV = Livingstone	COL = Colombo	SING = Singapore
CAI = Cairo	JO'B = Johannesburg	CAL = Calcutta	MAN = Manila
BEI = Beirut	BAH = Bahrain	KAG = Kagoshima	OK = Okinawa
KHA = Khartoum	KAR = Karachi	BK = Bangkok	TOK = Tokyo
ENT = Entebbe	BOM = Bombay	RG = Rangoon	

TABLE I.

CLEAR AIR TURBULENCE EXPERIENCED ON COMET FLIGHTS.

	LON-ROME		ROME-CAI/BEI		CAI/BEI-KHA		KHA-ENT		ENT-LIV		LIV-JO'B		CAI/BEI-BAH		BAH-KAR		KAR-BOM		BOM-COL		KAR-DELHI		DELHI-CAL		KAR-CAL		CAL-BK/RG		BK/RG-SING		BK-MAN		MAN-OK		OK-TOK	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
January	13	72	6	74	9	36	9	35	0	33	1	32	10	39	4	37	0	10	2	11	2	18	4	14	3	11	4	29	2	22	0	10	0	10	0	10
February	7	57	7	51	4	24	3	26	1	26	1	26	4	24	4	27	0	8	0	8	1	12	1	13	0	6	5	18	2	15	1	9	0	9	2	9
March	7	66	8	67	4	40	2	41	0	42	0	37	5	28	7	27	0	9	0	9	2	14	2	14	0	5	1	19	1	16	0	1	0	3	0	3
April	4	78	11	80	7	44	5	47	1	47	0	47	4	40	5	39	0	10	1	10	1	19	3	19	3	12	3	30	0	18	0	14	1	13	3	12
May	4	74	6	71	5	34	0	35	0	32	1	30	2	40	2	36	0	11	0	10	0	15	0	18	0	12	0	30	0	14	0	16	1	16	0	16
June	7	75	7	80	1	45	2	47	3	49	2	41	1	30	1	32	0	10	0	12	0	15	0	15	0	11	0	26	0	12	0	13	0	13	0	12
July	1	91	4	91	0	55	2	55	6	52	2	46	3	37	1	35	0	13	1	12	0	12	0	14	0	13	1	25	0	12	0	11	0	12	0	11
August	3	89	7	91	0	47	1	51	4	52	2	45	1	36	0	40	0	19	2	18	0	11	0	12	0	10	0	23	0	16	0	10	0	10	0	9
September	7	97	7	105	1	49	0	46	2	39	4	43	1	48	0	47	0	22	0	20	0	15	0	17	0	11	0	32	0	24	0	8	0	8	1	8
October	11	94	4	96	1	42	0	44	0	43	1	43	1	48	4	41	1	21	1	21	0	17	0	17	0	9	0	27	0	18	0	8	0	8	0	8
November	11	96	5	86	1	40	2	41	0	41	1	38	5	55	6	58	0	17	1	16	1	27	4	21	0	15	2	40	0	34	0	8	1	9	3	9
December	17	96	13	101	10	42	7	42	0	46	0	45	5	57	6	59	3	16	2	19	0	28	2	18	6	16	6	39	3	31	1	11	0	8	0	10

a = Total number of flights analysed over the sector.
b = Number of flights on which clear air turbulence was reported above 15,000 ft. irrespective of intensity or persistence.

bulence was reported as "moderate to heavy," the aircraft was fitted with a recording accelerometer and the peak acceleration increments recorded were $+0{\cdot}4g$ and $-0{\cdot}5g$. On no occasion was there difficulty in controlling the aircraft, neither was the turbulence considered to be sufficiently noteworthy for reference to be made to it in the Captain's Voyage Report.

Five of the nine cases were associated with jet streams and in some of the other cases the available data are insufficient to establish whether or not a jet stream existed over the sector. Two cases occurred in jet streams from N.W. and N. respectively over the Rome-London sector, two cases in north-westerly jet streams over the Bahrain-Beirut sector and one case in a jet stream from 260° over the Okinawa-Manila sector. In each case the wind was a headwind.

Table I indicates that clear air turbulence is experienced mostly in the winter months. A great many flights were made in and across the semi-permanent jet stream which, in mid-winter, lies between latitudes 26/30°N. from Africa to India and thence across to Japan. Over the Cairo/Beirut-Khartoum sectors, the aircraft crossed the jet stream approximately at right angles and near to the axis while over the Cairo/Beirut-Bahrain sectors, flight took place more in alignment with the axis and the aircraft thus was 'in' the jet stream for a much longer time. As a first approximation to the number of flights through or near jet streams, the mean vector wind over the cruise was evaluated for each flight from all available cruise winds as "found" by the Navigator and, if in excess of 100 knots, was assumed to be a jet stream.

Table III gives details for the individual sectors. A small number of cases included in the table, possibly, will not be true jet streams but, on the other hand, the mean vector wind from a number of flights operating in or near jet streams probably was less than 100 knots, especially on flights across the axis and a large number of the computed mean vector winds were in the 80/100 knots range. Table III, therefore, is probably an underestimate of the number of flights through jet streams, although the differences should not be large.

TABLE II.

CLEAR AIR TURBULENCE EXPERIENCED ON COMET FLIGHTS AND ASSOCIATION WITH JET STREAMS.

	LON-ROME	ROME-CAI/BEI	CAI/BEI-KHA	KHA-ENT	ENT-LIV	LIV-JO'B	CAI/BEI-BAH	BAH-KAR	KAR-BOM	BOM-COL	KAR-DELHI	DELHI-CAL	KAR-CAL	CAL-BK/RG	BK/RG-SING	BK-MAN	MAN-OK	OK-TOK
January	11 2 1 1	3 3 0 1	7 2 2 1	8 1 0 0		1 0 0 0	9 1 9 1	2 2 0 0		1 1 0 0	2 0 2 0	2 2 2 2	2 1 0 0	1 3 0 0	1 1 0 0			
February	5 2 0 0	4 3 1 0	4 0 1 0	2 1 0 0	1 0 0 0	1 0 0 0	1 3 1 3	3 1 1 0			1 0 0 0	1 0 0 0		3 2 0 0	1 1 0 0	1 0 0 0		0 2 0 2
March	4 3 0 0	6 2 2 0	4 0 1 0	2 0 0 0			3 2 2 1	3 4 0 1			1 1 0 1	2 0 1 0		0 1 0 0	0 1 0 0			
April	4 0 0 0	7 4 1 0	6 1 1 1	4 1 0 0	1 0 0 0		2 2 1 2	4 1 0 0		1 0 0 0	0 1 0 0	2 1 0 0	3 0 0 0	3 0 0 0			0 1 0 0	2 1 1 0
May	3 1 0 0	6 0 0 0	4 1 0 0			1 0 0 0	2 0 0 0	2 0 0 0									1 0 0 0	
June	5 2 1 0	3 4 0 0	1 0 0 0	2 0 0 0	3 0 0 0	2 0 0 0	1 0 0 0	1 0 0 0										
July	1 0 0 0	3 1 0 0		2 0 0 0	6 0 0 0	1 1 0 1	3 0 0 0	1 0 0 0		0 1 0 0				1 0 0 0				
August	2 1 0 0	4 3 0 0		0 1 0 0	3 1 0 0	1 1 0 0	1 0 0 0			2 0 0 0								
September	5 2 0 0	4 3 0 0	1 0 0 0		1 1 0 0	2 2 0 1	1 0 0 0											0 1 0 0
October	5 6 0 0	2 2 0 0	1 0 0 0			1 0 0 0	1 0 0 0	3 1 0 0	1 0 0 0	1 0 0 0								
November	8 3 1 2	2 3 0 0	1 0 0 0	2 0 0 0		0 1 0 0	3 2 2 1	6 0 0 0		1 0 0 0	1 0 1 0	3 1 0 0		2 0 0 0			1 0 0 0	1 2 1 2
December	11 6 0 1	8 5 0 0	8 2 2 0	6 1 0 0			1 4 0 0	6 0 0 0	2 1 0 0	1 1 0 0		1 1 0 0	4 2 0 0	6 0 0 0	3 0 0 0	1 0 0 0		
TOTAL	64 28 3 4	52 33 4 1	37 6 7 2	28 5 0 0	15 2 0 0	10 5 0 2	28 14 15 8	31 9 1 1	3 1 0 0	7 3 0 0	5 2 3 1	11 5 3 2	9 3 0 0	16 6 0 0	5 3 0 0	2 0 0 0	2 1 0 0	3 6 2 4

LEGEND: $\frac{p \mid q}{r \mid s}$

p = Number of flights on which clear air turbulence was reported below intensity "moderate".
q = Number of flights on which clear air turbulence was reported as intensity "moderate" or above.
r = Number of flights included under p on which mean cruise wind exceeded 100 knots (jet stream).
s = Number of flights included under q on which mean cruise wind exceeded 100 knots (jet stream).

Comparison of turbulence reports over the Cairo/Beirut-Khartoum and Khartoum-Entebbe sectors suggests that the incidence of clear air turbulence in crossing the jet stream over Africa is not appreciably greater than for areas where the jet stream is not found.

It can be said that the jet stream over the Cairo/Beirut-Bahrain sectors has been well explored by Comet aircraft. Many hours flying have taken place on the cold air side at altitudes approximating to, or a few thousand feet below, the altitude of the axis of the jet stream, *i.e.* in the quadrant reputed to be the most vulnerable to clear air turbulence. In general, this jet stream has comparatively low values of horizontal shear and comparatively high values of vertical shear.

It will be seen from Table III that, for the combined sectors, clear air turbulence was experienced on approximately 18 per cent. of occasions during flights through jet streams and that on only 7 per cent. of occasions (25 flights) was the intensity reported greater than "slight."

To summarise B.O.A.C. experience, clear air turbulence has been a relatively insignificant factor in day to day operations over the routes operated by the Comet I.

5. North Atlantic Routes

The association of clear air turbulence with jet streams may be of greater significance, however, to jet operations over North Atlantic routes for the following reasons:—

(*i*) Unlike routes to the south and east of the British Isles, only on rare occasions is cloud to be expected at altitudes covering the cruising range of an aircraft such as the Comet III (38-45,000 ft.) and clear air turbulence will, therefore, disturb an otherwise smooth flight.

(*ii*) There is a relatively high frequency of frontal jet streams at the extremities of the route with

TABLE III.

JET STREAMS ENCOUNTERED DURING COMET SERVICES AND ASSOCIATED CLEAR AIR TURBULENCE.

		LON-ROME	ROME-CAI/BEI		CAI/BEI-KHA		LIV-JO'B		CAI/BEI-BAH		BAH-KAR	KAR-DELHI		DELHI-CAL	KAR-CAL	CAL-BK/RG	OK-KAG			KAG-TOK		
		a	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*a*	*b*	*a*	*a*	*a*	*a*	*b*	*c*	*a*	*b*	*c*
January	*d*	2	8	1	10	1			25	7	16	4	1	11	3	1	2	4		3	6	1
	e	2	1	0	3	0			9	1	0	2	0	4	0	0	0	0		0	0	0
February	*d*		9	1	7		1		14		8	1		1			3	1	1	5	5	1
	e		1	0	1		0		5		1	0		0			0	0	0	2	0	0
March	*d*	1	5	2	9		3		16	2	3	3		1			1			2		
	e	0	1	1	1		0		3	1	1	1		1			0			0		
April	*d*		5		5		1	1	8		2						1			7		
	e		1		2		0	0	2		0						0			1		
May	*d*				1		3		1								1	1		3	1	
	e				0		0		0								0	0		0	0	
June	*d*	2					7													1		
	e	1					0													0		
July	*d*						2															
	e						1															
August	*d*	2					9	1														
	e	0					0	0														
September	*d*	4					3															
	e	0					1															
October	*d*	5			1		3		1											1		
	e	0			0		0		0											0		
November	*d*	11	1				1	1	7			2						1		6	2	
	e	3	0				0	0	2			1						0		3	0	
December	*d*	1	4		7		1		12		3			3	1	1	4			5	4	
	e	1	0		2		0		0		0			0	0	0	0			0	0	
TOTAL	*d*	28	32	4	40	1	34	3	84	9	32	10	1	16	4	2	12	7	1	33	18	2
	e	7	4	1	9	0	2	0	21	2	2	4	0	5	0	0	0	0	0	6	0	0

a = Mean cruise wind 100-140 knots.

b = Mean cruise wind 140-180 knots.

c = Mean cruise wind greater than 180 knots.

d = Number of flights with mean cruise wind as specified.

e = Number of flights included under *d* on which clear air turbulence was reported.

NOTE:—The sector Okinawa-Tokyo was flown "Airways," and has been sub-divided into Okinawa-Kagoshima and Kagoshima-Tokyo to obtain a more realistic indication of jet stream cases.

the possibility of "severe" turbulence being encountered during climb and descent.

(*iii*) There is difficulty for an aircraft in flight to identify jet streams and, unlike the semi-permanent winter jet streams of lower latitudes, over the North Atlantic they may occur at any time of the year and from any direction (although most frequently from directions between S.W. and N.W.). Perhaps on occasions cloud structure, *e.g.* sheet of cirrostratus associated with well marked warm front, would prove useful in such identification but the temperature method widely used at the present time at 20,000/25,000 ft. cannot be applied at levels above the jet stream axis. Below the axis (which is usually at about 30,000 ft. over the North Atlantic routes) the strong wind belt is found in the warm air in a well marked frontal zone and temperature discontinuities of 10°C. or more often occur at the front. At about 30,000 ft., however, and often below this altitude, the tropopause is reached in the cold air and the temperature lapse is checked, while temperature continues to fall in the warm air, owing to the higher tropopause in this air mass. Thus, the temperature difference on the "warm" and "cold" sides of the jet stream axis is reduced and at some height above the axis, the temperature on the "warm" side may be less than that on the "cold" side. In general there is no marked discontinuity of temperature at or just above the jet stream axis to enable the zone to be identified in flight. For this reason, and in view of the doubtful advantages to be gained from the winds, in-flight searching for the jet stream will seldom, if ever, be undertaken by a jet aircraft on a scheduled passenger service.

In February 1954, the author had the privilege and pleasure of visiting the works of Short Bros. & Harland Limited, at Belfast, and had the opportunity of discussing the clear air turbulence problem at some length with the test pilots, who frequently fly over the N.W. districts of the British Isles up to altitudes of 50,000 ft. The test flights are usually undertaken in areas corresponding approximately to end of climb and start of cruise for trans-Atlantic jet operations from London and a statistical analysis of turbulence over those areas, therefore, is of great interest to B.O.A.C. Accordingly, advantage was taken of the offer made by the test pilots to supply routine reports of turbulence encountered in flight and a turbulence report (subjective in the absence of recording accelerometers) is now made out on a standard B.O.A.C. turbulence *pro-forma* and copies are sent to B.O.A.C. and to the Meteorological Office, Air Ministry. An analysis of the reports received so far is given in Table V and supports previous findings that "severe" clear air turbulence during the summer months is infrequent. There was nil "very severe" turbulence reported and the only "severe" case occurred in May in a zone of well marked wind shear associated with a jet stream. It is noteworthy, however, that the turbulence occurred below the axis of the jet stream and on the high pressure side.

A summary of turbulence encountered during the twelve months ending February 1954 was prepared by E. A. Hyde, based largely on his own personal experience, and has been published. Reference to this summary has already been made in Section 3.

Hyde quoted four instances of very severe or violent turbulence and confirmed that "severe" turbulence is not always associated with jet streams and that flights through or near jet streams were often smooth. He stated also that topography (*e.g.* Lake District) seemed to play a part in intensifying turbulence.

The four cases of "violent" turbulence occurred in remarkably similar weather situations and, therefore, deserve special mention. In each case there was a cold low and associated trough in mid-Atlantic moving eastwards with a developing thermal ridge over the British Isles. The turbulence occurred in warm air and close to the axis of the ridge. The Atlantic troughs to the west were associated with large thermal gradients and very cold air on the west side was advected well south into the Atlantic. Examination of the upper air data reveals that three of the cases occurred below the axis and on the high pressure side of a jet stream while the fourth occurred above the axis on the low pressure side, *i.e.* in regions of the jet stream where comparatively little severe turbulence has been reported. There are indications also that the turbulence occurred in the following longitudinal regions of the jet stream:—

(*a*) Near the exit in an area of marked difluence,

(*b*) At a fork where the jet stream splits into two or more parts,

or (*c*) In an area where the jet stream curves or bends.

Comparatively little is known of the dynamical flow in these complex areas and their possible association with turbulence would seem to merit further investigation.

Several authors, *e.g.* Sawyer[17], have discussed the phenomenon of dynamic instability which occurs when the anticyclonic wind shear exceeds the local value of the Coriolis parameter and it is possible that large local values of isentropic wind shear were realised in these cases, but the nature of any turbulent motion resulting from such instability is not apparent.

Murray and Daniels[18] examined the wind structure of about fifty jet streams over the British Isles and found that the mean component of transverse flow to the right (*i.e.* from low to high pressure) in the exit region was 7·3 knots on the cold side and 12 knots on the warm side. They stated also that transverse flow of this nature was consistent with an "indirect" circulation (*i.e.* vertical motion upwards in cold air and downwards in warm air) above and below the axis of the jet stream. The analysis indicated also that the mean pressure at exits to jet streams was 27 mbs. higher (*i.e.* about 2,000 ft. lower) than the mean pressure at entrances, although the values refer to different jet streams since in none of the cases analysed was it possible to obtain data on the entrance and exit to the same jet stream.

TABLE IV.

CLEAR AIR TURBULENCE REPORTED AS EXCEEDING INTENSITY "MODERATE" BY B.O.A.C. COMET AIRCRAFT.

Ref. No.	*Sector Time (G.M.T.) Date*	*Pressure altitude (thousands of feet)*	*Intensity and Location*	*Remarks*
1.	Rome-London 05.50 to 06.45 6th November 1952	36 to 39.5	Moderate to severe. The turbulence commenced at Genoa and increased towards Geneva whence it persisted with steady amplitude until a cold front was passed in the Paris area when it stopped quite suddenly.	Well marked warm front from South of Iceland to Brest thence as a cold occlusion to Paris and Sweden. North-westerly jet stream ahead of warm front and at 09.00Z, Leuchars reported 153 knots and Hemsby 124 knots at 30,000 ft. The turbulence occurred downwind and above the level of the axis of the jet stream. Cloud was mainly stratiform and tops were at least 5,000 ft. below level of aircraft. "Moderate" turbulence (accn. increments on the Kollsman accelerometer $\pm 1g$) was also reported by another Comet aircraft flying over this sector on 6th November 1952. Turbulence commenced at 07.45Z at 37,000 ft. over the Alps and lasted for 20 minutes. The pilot stated that a very marked wind change from W. to N. (corresponding with a bend in the streamlines) occurred during the approximate time of the turbulence.
2.	Rome-London 10.15 to 11.10 7th November 1952	35 (mean)	Severe. Turbulence was experienced from Genoa to Dijon and was sudden in onset. The readings of the Kollsman accelerometer averaged $+4g$ to $-3g$, while one bump registered $+6g$. There were occasional periods of about 1 minute when turbulence ceased.	There was an intense north-westerly jet stream over the U.K. and France and the 200 mb. chart indicated a cold low over Scandinavia with a trough extending to the Western Mediterranean. The turbulence occurred near the exit of the jet stream. The cruise wind found by the aircraft was 320/160 (degrees/knots). Cloud over the Alps was Ac. As. tops about 20,000 ft.
3.	Beirut-Rome 05.30 to 06.30 1st December 1952	37 to 38	Moderate to severe. Over the second half of the cruise.	No special features were observed in the upper air pattern and there was no evidence of high values of wind shear. It is probable that the turbulence occurred near the tropopause.
4.	Karachi-Calcutta 01.10 to 02.00 28th January 1953	32 to 33	Moderate to severe. The turbulence commenced at top of climb and continued as far as Bhopal (77°E.).	No special features in the meteorological situation for this time of the year. Aircraft winds were 310/100 from 69°E. (25,000 ft. on climb) to 73°E. and 280/95 from 73°E. to Bhopal and there was nil cloud. A recording accelerometer was carried on this flight and accn. increments of $+0{\cdot}4g$ and $-0{\cdot}5g$ were recorded.
5.	Bahrain-Beirut 00.30 16th February 1953	39 to 38·5	Moderate to severe. Turbulence commenced at top of descent and ceased on descent to 38,500 ft.	The upper air charts show a cold trough over Europe and a complex cold pool over the Western Mediterranean moving slowly eastwards. The associated jet stream over the Mediterranean likewise was propagated eastwards as illustrated by the following observations: 03.00 *G.M.T.* — *Height* — 15.00 *G.M.T.* — *Height* °/*knots* — °/*knots* Malta 258/165 218 mb.* — — Nicosia 272/78 250 mb. 247/120 250 mb. 285/144 200 mb. 249/124 200 mb. 275/162 175 mb.* — — Habbaniyah 328/58 250 mb. 310/63 250 mb. 328/79 200 mb. 307/120 205 mb.* *=maximum wind. From the 03.00 Nicosia and 15.00 Habbaniyah observations, it would appear that the turbulence occurred near the jet stream axis in a zone of pronounced vertical wind shear (note that wind speeds at 38/39,000 ft. were almost double those at 34,000 ft.). Aircraft cruise winds were 330/100 and 320/115.
6.	Rome-Beirut 15.30 to 16.30 27th February 1953	35 to 36	Moderate to severe "cobblestones." The turbulence was almost continuous between 18°E. and 24°E.	There was an upper low over the eastern Black Sea and an associated trough extended to the Gulf of Sirte. Cold air penetrated the Eastern Mediterranean and temperature on descent into Beirut was −46°C. at 30,000 ft. and −31°C. at 20 000 ft. On climb out to Bahrain temperatures were −45°C. and −29°C. respectively, thus confirming the descent readings. The upper air data suggest that the turbulence occurred near the tropopause in a region of difluence.

TABLE IV—*Continued.*

Ref. No.	*Sector Time (G.M.T.) Date*	*Pressure altitude (thousands of feet)*	*Intensity and Location*	*Remarks*
7.	Bahrain-Beirut 21.00 to 21.30 10th April 1953	34 to 36	Moderate to severe over the central portion of the cruise.	The upper air charts indicate a jet stream from 260° near Bahrain at 15.00Z on 10th April 1953 with axis at approximately 38,000 ft. There was an unusually strong thermal gradient at the cruising altitudes from Bahrain to the north-west as shown by the following observations:— 15.00Z, 10*th April* 1953 — *Bahrain* — *Habbaniyah* 300 mb. — −29°C. — −47°C. 250 mb. — −39°C. — −53°C. 200 mb. — −51°C. — −51°C. *Tropopause* — 55,000 ft. — 34,000 ft. The turbulence occurred on the low pressure side and below the axis of the jet stream in a region where contours showed cyclonic curvature (upper air trough). There is evidence also that the turbulence occurred near the tropopause in an area where the height of this surface was a minimum. In this respect it is interesting to note that the forecast indicated the tropopause surface as intersecting the flight path at about mid-cruise and intermittent "moderate" clear air turbulence was forecast for the central portion of the cruise.
8.	Okinawa-Manila 20.30 to 20.50 15th April 1953	36 (mean)	Moderate to severe from 23°N. to 21°N.	There was a wave disturbance just south of Japan and the cold front had passed through Okinawa some two hours before the aircraft departed. The turbulence occurred in the associated jet stream on the warm air side and below the axis. There was nil cloud over the cruise.
9.	Rome-London 05.40 to 06.40 11th January 1954	37 to 39	Continuous moderate turbulence over the Alps from 05.40 to 05.50 with occasional "moderate to severe" bumps. Readings of the Kollsman accelerometer were in the range $+3\frac{1}{2}g$ to $-1g$. North of the Alps there was intermittent "slight to moderate" turbulence. The turbulence occurred for periods of 2 to 5 minutes followed by 3 to 5 minutes smooth flying.	There was a well developed jet stream from about 350° extending from Norway to the Alps at a mean longitude of 10°E. The turbulence occurred just above the axis and on the high pressure side of the jet stream. The surface chart indicated a warm front over Central France which was moving south-east. Occasional thin Ci. was noted during cruise and at times the aircraft was in cloud.

TABLE V.

CLEAR AIR TURBULENCE EXPERIENCED BY CANBERRA AIRCRAFT IN TEST FLIGHTS FROM BELFAST BY SHORT BROTHERS AND HARLAND LIMITED. SPRING AND SUMMER, 1954.

	Nil	*"Slight"*	*"Moderate"*	*"Severe"*	*"Very Severe" (or "Violent")*
March	9	2	5	0	0
April	12	2	0	0	0
May	17	9	2	1	0
June	18	2	2	0	0
July	6	1	0	0	0
August	*Nil high altitude flying*				
September	13	0	1	0	0

CASE OF "SEVERE" TURBULENCE:

"Severe" turbulence occurred over S.E. Ireland at 20,500 to 22,000 ft. at approximately 15.00Z on 4th May 1954, but at the same altitude in the Rathlin Island area it was "moderate". The following upper air observations suggest that the turbulence occurred in a region of strong wind shear and below the axis and on the high pressure (warm air) side of a north-westerly jet stream.

		15.00Z *Valentia*		14.00Z *Aldergrove*		14.30Z *Camborne*		14.00Z *Liverpool*		09.00Z *Worcester*
Height	*Pressure altitude*	*Wind*	*Temp. °C.*	*Wind*	*Temp. °C.*	*Wind*	*Temp. °C.*	*Wind*	*Temp. °C.*	*Temp. °C.*
	ft.									
500 mb.	18,000	315/61	−19	330/43	−21	336/62	−18	029/12	−27	−31
450 mb.	21,000	305/58	−24	334/78	−26	343/78	−24	346/15	−33	
400 mb.	23,500	309/62	−30	326/93	−31	335/90	−29	338/42	−38	−38
300 mb.	30,000	305/65	−44	325/98	−43	328/103	−41	338/98	−46	−45
250 mb.	34,000	300/82	−59	327/100	−51	329/116	−48	339/55	−48	
262 mb.	33,000					330/144				

Evidence for an indirect vertical circulation at the jet stream exit was provided by Johnson and Daniels[19] in a study of rainfall in relation to jet streams. Atmospheric circulations resulting from acceleration terms in the equations of motion, variations in the height of the jet stream axis and horizontal curvature of the axis may well be significant factors in the occurrence of clear air turbulence near jet streams, but in the present state of knowledge it is difficult to visualise the physical processes involved.

The four cases of "violent" turbulence already mentioned and two others of special interest will now be discussed in greater detail. The upper air charts, observational data from upper air stations and "notes on the aerological situation" are extracted from the Daily Aerological Record of the Meteorological Office, London. A chart indicating the location of the upper air stations is shown in Fig. 7.

CASE 1.

Very severe turbulence experienced by a Canberra aircraft at 26,000/28,000 ft. over the North Channel on 23rd May 1953. Exact time unknown but probably during the afternoon.

The 300 mb. chart for 15.00 G.M.T. is shown in Fig. 1.

Notes on aerological situation. "The warm thermal ridge over the British Isles and France is still developing slightly. The air in the southern tip of the trough in the Atlantic is exceptionally cold for May near the Azores."

There is evidence of a jet stream, approximately S.W. through Stornoway with the axis at 300 mb. or a little higher. At 03.00 G.M.T. the jet stream was approximately S.W. through Aldergrove and with the development of the thermal ridge, it moved N.W. The turbulence occurred below the axis and on the high pressure side of the jet stream in an area where the streamlines showed slight anticyclonic curvature.

CASE 2.

Very severe turbulence experienced by a Canberra aircraft at 22,000/23,500 ft. over the North Channel on 26th October 1953 at 14.45 G.M.T.

The 500 mb. and 300 mb. charts for 15.00 G.M.T. are shown in Figs. 2(*a*) and 2(*b*) respectively.

Notes on aerological situation. "The spread N.N.E. of warm air over the British Isles was continued. The trough which extended from Greenland into the mid-Atlantic moved further East and very cold air was advected in the eastern and central Atlantic. The 17,400 ft. total thickness line indeed penetrated as far south as 47°N. (longitude 20/25°W.), which exceeded the minimum thickness value recorded there for October in the five year period 1946/50. The jet stream on the southern and eastern flanks of the Atlantic cold trough intensified, 146 knots being reported from the Ocean Weather Ship at 61°N. 15°W. at 15.00Z."

The observations from O.W.S. "I" suggest that a southerly jet stream was close to this station at 15.00 G.M.T. and that the axis was at approximately 300 mb. The 300 mb. chart indicates the probability of a jet stream at about latitude 45°N. near the cold trough possibly splitting into two branches to the N. and N.E. respectively. The turbulence occurred in an area of pronounced difluence, and in relation to the jet stream through O.W.S. "I," was below the axis and on the high pressure side as in Case 1.

CASE 3.

Very severe turbulence experienced by a Canberra aircraft at 22,000/24,500 ft. over the North Channel on 21st December 1953 at 15.15 G.M.T.

The 500 mb. and 300 mb. charts for 15.00 G.M.T. are shown in Figs. 3(*a*) and 3(*b*) respectively.

Notes on aerological situation. "The strong zonal flow extending across America to the Atlantic persisted, while the trough on the West Atlantic moved steadily eastwards. The ridge immediately down wind, *viz.* the one near the British Isles, grew quickly in amplitude as it moved eastwards."

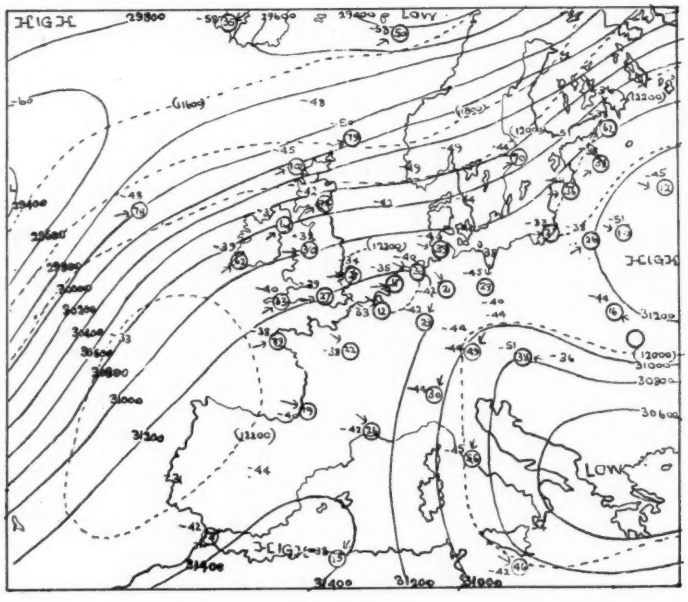

FIGURE 1. 300 mb. Contour Chart, 15.00 G.M.T., 23rd May 1953.

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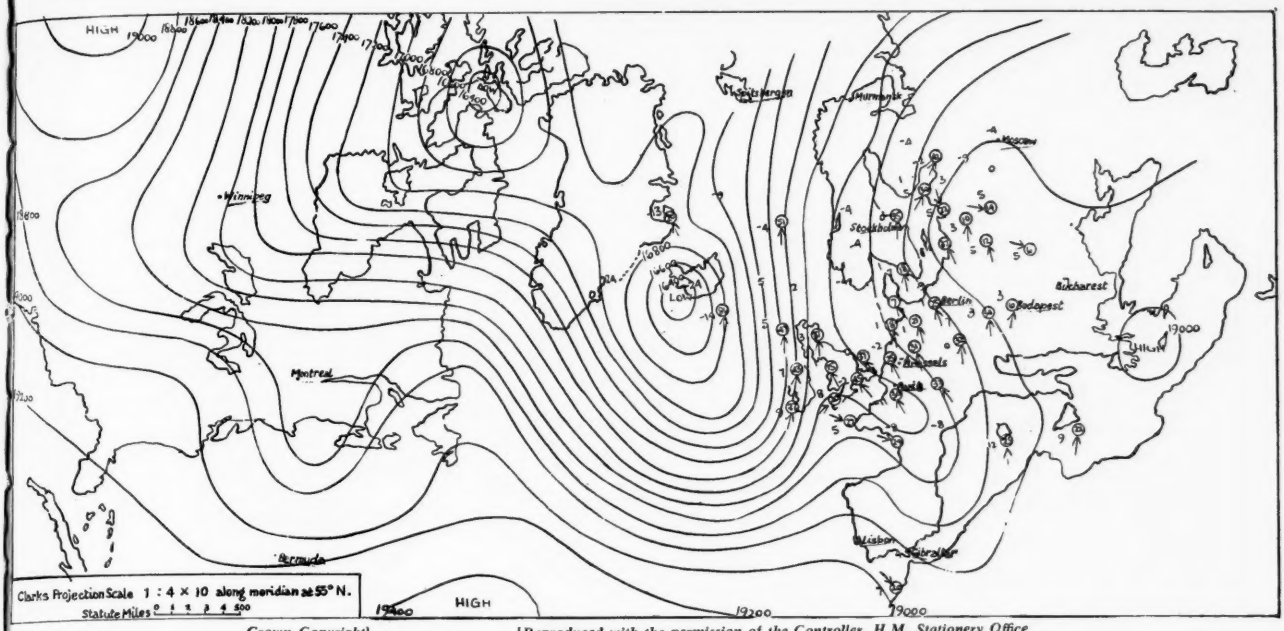

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FIGURE 2(*a*). 500 mb. Contour Chart, 15.00 G.M.T., 26th October 1953.

The 15.00 G.M.T. charts show evidence of a south-westerly jet stream just west of O.W.S. "J" with the axis bending to N.W. through Stornoway. The height of the axis appears to be about 300 mb. or slightly higher. The turbulence occurred below the axis and on the high pressure side as in the two previous cases. The streamlines at 400 mb., which was the mean level at which the turbulence was experienced, showed anti-cyclonic curvature as illustrated by the following wind observations:—

400 mb.	15.00Z	21.00Z
O.W.S. "J"	213/88	230/99
Aldergrove	286/55	244/43
Stornoway	287/83	251/52
Valentia	243/34	—
Camborne	317/29	285/22

CASE 4.

Very severe turbulence experienced by a Canberra aircraft at 33,000/34,000 ft. over the Solway Firth on 20th February 1954 at 12.50 G.M.T.

The 300 mb. charts for 03.00 G.M.T. and 15.00 G.M.T. are shown in Figs. 4(*a*) and 4(*b*) respectively.

Notes on aerological situation. "The developing thermal ridge moved east into the British Isles. Intense cold air advection occurred in mid-Atlantic, resulting in a total thickness of 16,500 ft. at Ocean Weather Ship 'C'—a value not reached in any of the three preceding years."

The upper air charts for 03.00 G.M.T. suggest the existence of a fork in the south-westerly jet stream in mid-Atlantic (or perhaps a double jet stream), one branch proceeding in a north-easterly direction to an

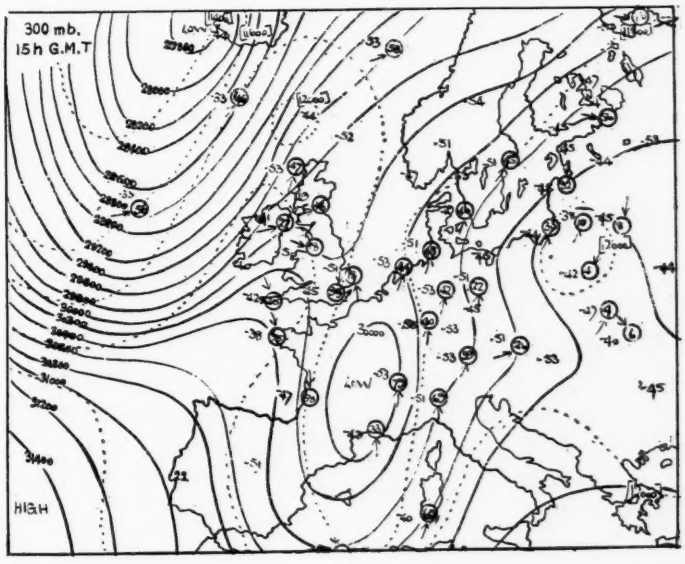

FIGURE 2(*b*). 300 mb. Contour Chart, 15.00 G.M.T., 26th October 1953.

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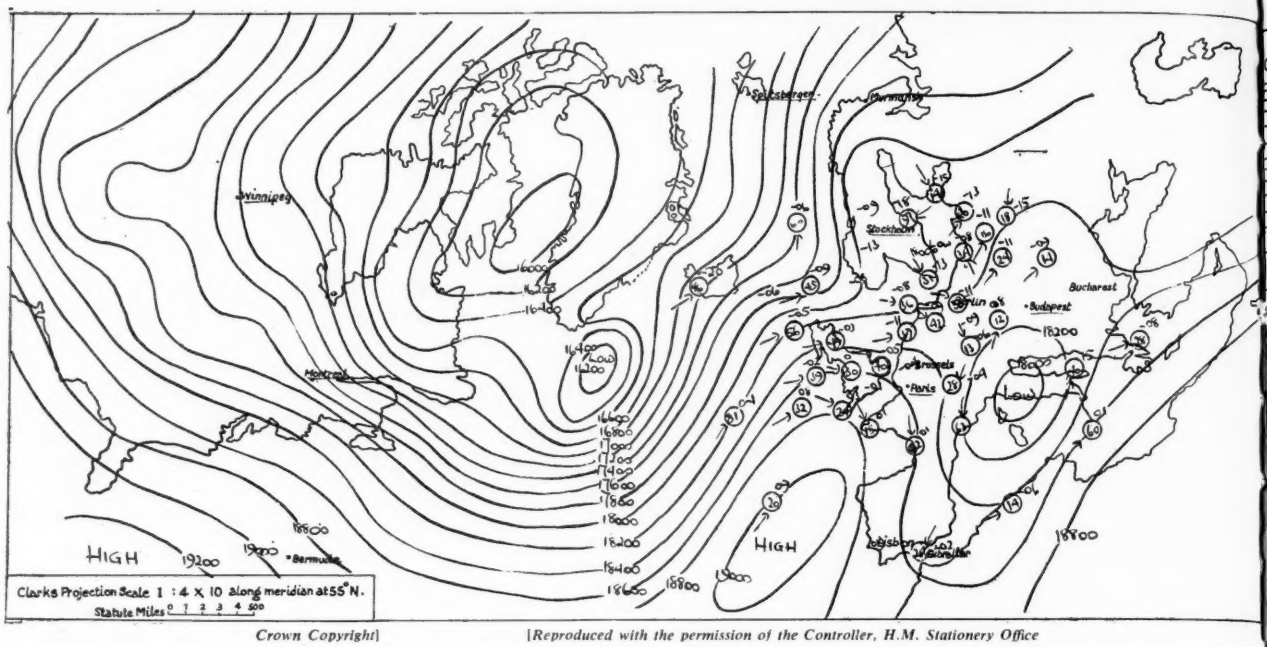

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FIGURE 3(*a*). 500 mb. Contour Chart, 15.00 G.M.T., 21st December 1953.

exit to the south of Iceland and the other branch proceeding north of O.W.S. "J" then turning to the right and becoming N.W. to N.N.W. just off S.W. Ireland and Brest and thence into N.W. Africa.

It would be interesting to know if there was any high level clear air turbulence over the Prestwick-Keflavik sector on the morning of 20th February 1954.

With the development of the thermal ridge to the west of the British Isles, the northern jet stream was displaced north-westwards to the Keflavik area and the winds backed to a more southerly point. With the eastward movement of the ridge, the bend in the southern branch of the jet stream was displaced northeastwards and at 15.00 G.M.T. reached a point just north of Stornoway and the north-north-westerly jet stream, with its axis at approximately 300 mb., extended from east of Stornoway to just west of Liverpool and thence became northerly between Brest and Bordeaux and across eastern Spain.

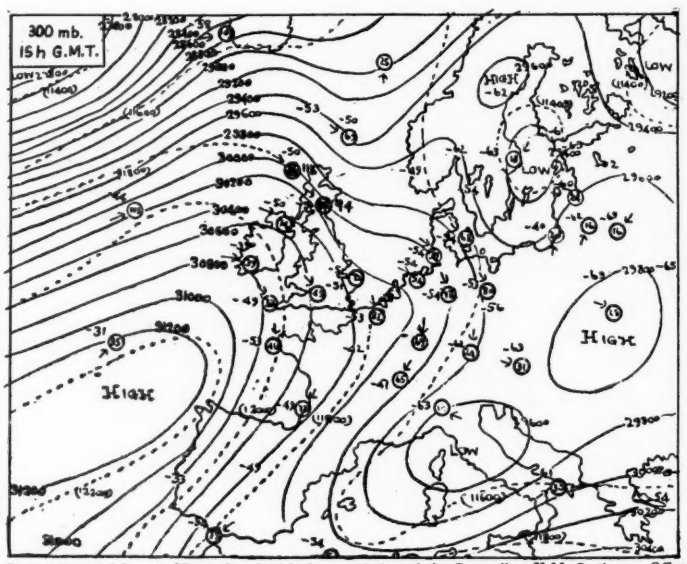

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FIGURE 3(*b*). 300 mb. Contour Chart, 15.00 G.M.T., 21st December 1953.

The turbulence occurred above the axis of the north-north-westerly jet stream and on the low pressure side in an area where the streamlines showed anticyclonic curvature.

CASE 5.

Very severe turbulence experienced by a Meteor aircraft at 22,000/30,000 ft. about 25 miles north-west of Valley on 29th December 1951, at 08.45 G.M.T.

The 300 mb. charts for 03.00 G.M.T. and 15.00 G.M.T. are shown in Figs. 5(*a*) and 5(*b*) respectively.

The upper air observations indicate that an intense north-westerly jet stream, with axis at approximately

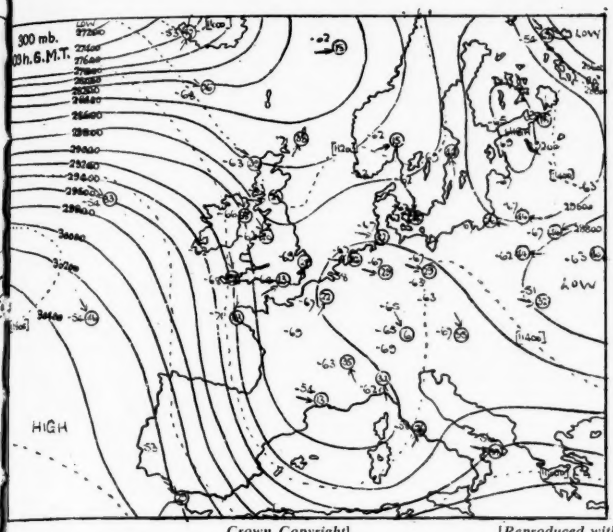

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FIGURE 4(*a*). 300 mb. Contour Chart, 03.00 G.M.T., 20th February 1954.

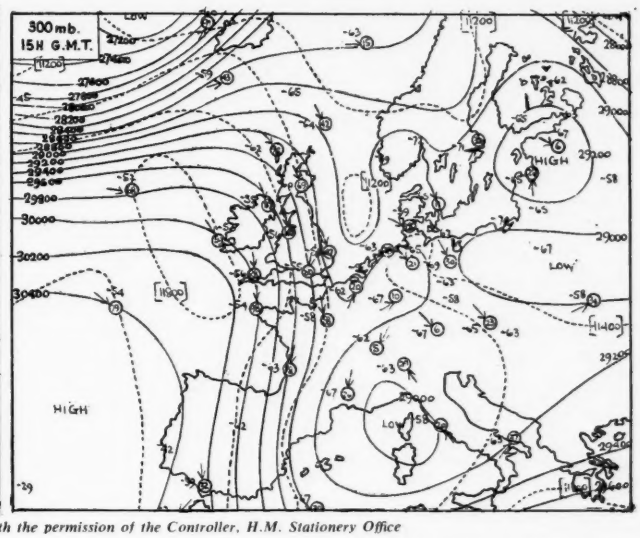

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FIGURE 4(*b*). 300 mb. Contour Chart, 15.00 G.M.T., 20th February 1954.

300 mb. or slightly higher, was close to Aldergrove at 09.00 G.M.T. As frequently happens, the jet stream was propagated along its length during the course of the day as the wind observations on p. 626 indicate. It would appear, therefore, that the turbulence was encountered in the exit region of the jet stream. In addition, the contours suggest the possibility of a fork in the jet stream with one branch proceeding in a south-south-west direction towards the Pyrenees.

CASE 6.

The most severe case of clear air turbulence reported by captains of B.O.A.C. Comet aircraft in over 25,000 hours flying was over the Rome-London sector on 7th November 1952 and the case has been discussed in Table IV.

The axis of the jet stream over the U.K. appears to have been approximately 35,000 ft. and from the 300 mb. chart for 03.00 G.M.T., which is shown in Fig. 6, it may be deduced that the turbulence occurred near the jet stream axis in the exit region. A bend in the streamlines is also indicated in this region.

6. Forecasting

In the absence of well-defined forecasting rules, forecasters in general have not ventured to indicate

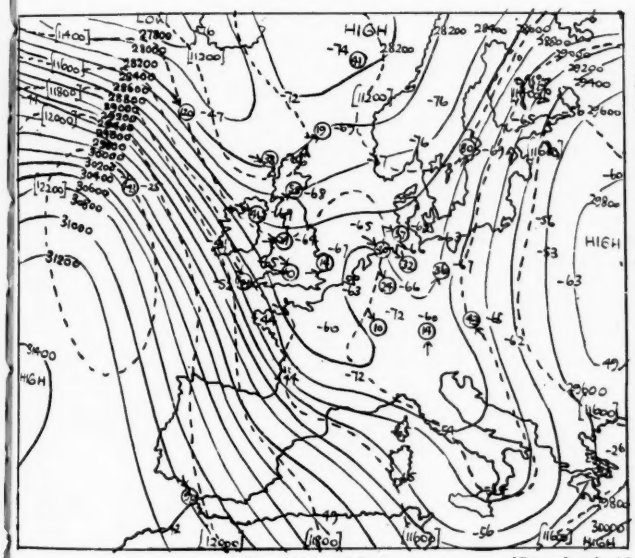

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FIGURE 5(*a*). 300 mb. Contour Chart, 03.00 G.M.T., 29th December 1951.

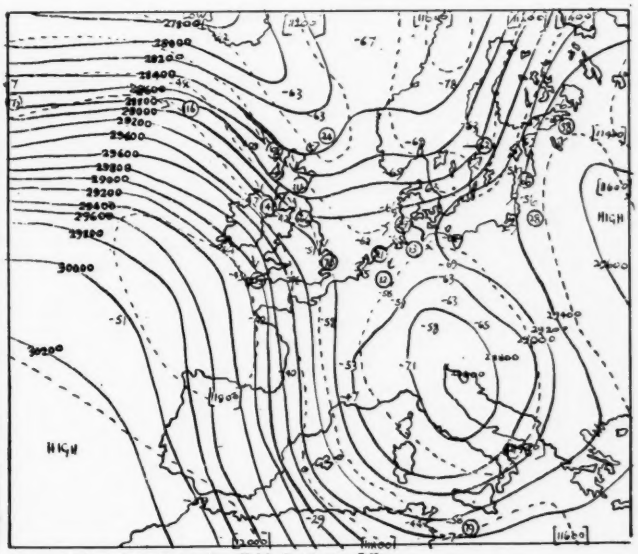

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FIGURE 5(*b*). 300 mb. Contour Chart, 15.00 G.M.T.,

CASE 5—WIND OBSERVATIONS

Pressure	*Pr. Alt.*	*Aldergrove*		*Liverpool*			*Hemsby*		
(*mb*)	(*feet*)	03.00	09.00	03.00	09.00	15.00	09.00	15.00	21.00
450	21,000	250/20	310/60	220/20	230/30	320/105	220/15	220/30	330/85
400	23,500	230/35	310/110	240/20	280/35	320/105	220/15	230/30	330/110
350	27,000	220/45	310/140	250/25	320/70	320/140	230/15	270/30	330/135
300	30,000	270/45	320/150	260/25	320/97	320/165	250/20	320/70	330/135

likely areas of clear air turbulence in route forecasts. In the present state of knowledge, it is considered that, as a very necessary first step, the position and intensity of jet streams should be marked on actual and forecast upper air charts at and above 500 mb. It is regrettably true that there is often insufficient basic meteorological information to indicate whether or not a jet stream exists in an air stream of high wind speeds and complex situations arise from time to time of which comparatively little is known, *e.g.* double jet streams or jet streams split into two or more "fingers." However, it cannot be denied that there are many occasions, particularly over the U.K., where reliable upper air observations are available well into the stratosphere, when jet streams can be identified and, since their displacement often is associated with that of a slow moving warm front, forecast error of position normally should not be large.

The use of the "jet stream" as a parameter in upper air analysis is an operational requirement likely to become increasingly important with the expansion of civil jet operations. Unfortunately, there is a tendency to associate the term "jet stream" with any region of strong winds exceeding, say, 80 to 90 knots. It is to be hoped that the W.M.O. will soon issue a standard definition of the jet stream to clarify the situation. A necessary condition to be fulfilled is that the wind speed should decrease radially in all directions from the axis.

7. Conclusions

(*i*) Previous statistical analysis of reports on "severe" clear air turbulence over the U.K. and certain other parts of the world revealed that a substantial number of cases occurred in areas of pronounced wind shear (in the vertical and/or the horizontal), very often in association with jet streams. Many other flights through such areas, however, experienced nil turbulence and, conversely, severe turbulence was experienced in areas where the wind shear was small. The majority of cases of "severe" turbulence near jet streams occurred either below the axis on the cold air side or above the axis on the warm air side and these "quadrants" usually correspond to areas of maximum wind shear. Cases of "severe" turbulence below the axis and in the warm air were very rare. It should be noted, however, that of the five cases of "very severe" turbulence referred to in Section 5, three occurred below the axis on the warm air side and a fourth above the axis on the cold air side.

(*ii*) Comet aircraft of B.O.A.C. operating over the London/Far East and London/South Africa routes have encountered clear air turbulence exceeding intensity "moderate" only on rare occasions and the general level of turbulence has been much more pronounced in cloud than in clear air. Notwithstanding the fact that the aircraft were flown for many hours in or across jet streams, and in areas of strong wind shear, there has not been a single "incident report" resulting from clear air turbulence.

(*iii*) The incidence of clear air turbulence is a maximum, but is not necessarily the most severe, during mid-winter, while it is comparatively rare during mid-summer. Over N.W. Europe, a number of the more severe cases have occurred in November. During this month, penetration southwards of Arctic air may set

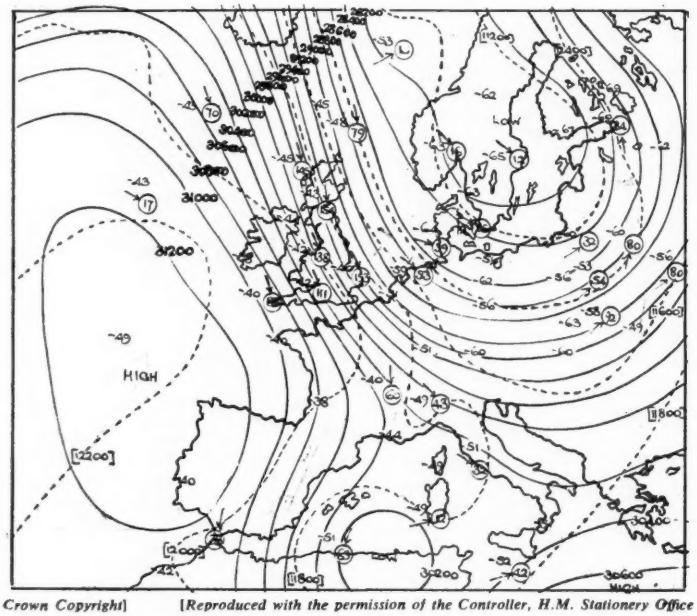

FIGURE 6. 300 mb. Contour Chart, 03.00 G.M.T., 7th November 1952.

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up large thermal gradients and areas of strong wind shear.

(*iv*) From experience of Comet aircraft, nil or only occasional slight turbulence is normally found in the semi-permanent jet stream which extends from about 26°N in Africa to Southern Japan in winter. Slight turbulence is often encountered when flying through the tropopause in these latitudes.

(*v*) Clear air turbulence may be of significance to jet operations over the North Atlantic and an analysis of reports of "very severe" turbulence indicates that, over areas corresponding to climb out and beginning of cruise on westbound trans-Atlantic jet operations from London, such turbulence may be encountered in regions of strong wind shear associated with well developed jet streams, particularly from a north-westerly direction, and in warm air near the axis of thermal ridges in advance of deep cold troughs moving eastwards across the Atlantic. It is possible that the two types are closely connected and that clear air turbulence in its severest form may often occur near the exit of a well developed jet stream, or in an area associated with a "fork" or "bend" in the axis. Our knowledge of the dynamics of complex jet streams, however, is insufficient at the

TABLE VI.

ACCELEROMETER READINGS ON COMET FLIGHTS.

A. GUSTS OF ±1*g* OR MORE:

Date	*Peak acceleration increments*	*Sector*	*Location*	*Remarks*
9th July 1952	+1·0*g*	Livingstone-Johannesburg	On descent at 23,000 ft.	Severe turbulence in Cu. Nim.
31st October 1952	−1·3*g*	Rome-Beirut	On climb at 9,000 ft.	"Violent" turbulence in Cu. Nim.
9th March 1953	+1·0*g*	Livingstone-Entebbe	Top of descent at 36,000 ft.	Severe turbulence in Cu. Nim.
6th April 1953	+1·1*g**	Livingstone-Entebbe	Mid-cruise at 35,000 ft.	Thick Cs. with embedded Cu. Nim. Very severe turbulence.
5th August 1953	+1·1*g*	Delhi-Karachi	On descent at 20,000 ft.	Thick layer cloud and Cu. Nim. Very severe turbulence. Aircraft diverted to Nawabshah.
27th October 1953	−1·0*g*	Tokyo-Okinawa	Approaching top of descent at 35,000 ft.	"Heavy" turbulence in Cu. Nim., tops above 40,000 ft.

*Two bumps of this intensity were recorded at approximately 7½°S. 30°E. (just west of the southern part of Lake Tanganyika) where the ground rises some 5,000 ft. above the Lake. This is an area well known for localised "build-up" of Cumulo-Nimbus in an unstable easterly air stream.

B. CLEAR AIR GUSTS:

Date	*Sector*	*Pressure altitude (ft.)*	*Peak acceleration increments (g)*		*Corresponding gust speeds* (ft./sec. E.A.S.)*		*Remarks by Aircraft Commander. c.a.t.= clear air turbulence*
			+	−	*Up*	*Down*	
13th January 1953	Bombay-Colombo	34,000	0·4	0·2	13	7	Moderate c.a.t. at top of climb.
28th January 1953	Karachi-Calcutta	31,000	0·4	0·5	14	18	Moderate to heavy c.a.t. at top of climb to Bhopal.
24th June 1953	Rome-Cairo	35,000	0·3	0·3	8	8	Moderate c.a.t. north of El Adem.
24th Sept. 1953	Rome-London	35,000	0·5	0·4	13	10	Moderate c.a.t. over Alps. 8/8 Cs. below.
26th Sept. 1953	London-Rome	39,000	0·5	0·3	20	12	Moderate c.a.t. above Cs. (tops 32,000 ft.). Persistent over first half of cruise.
6th October 1953	London-Rome	39,000	0·3	0·6	8	16	Moderate turbulence with downdraught over Alps. Nil cloud.
8th October 1953	London-Rome	38,000	0·3	0·3	9	9	Moderate c.a.t. over Alps.

*Calculated by the method of Air Publication 970, Chapter 203.

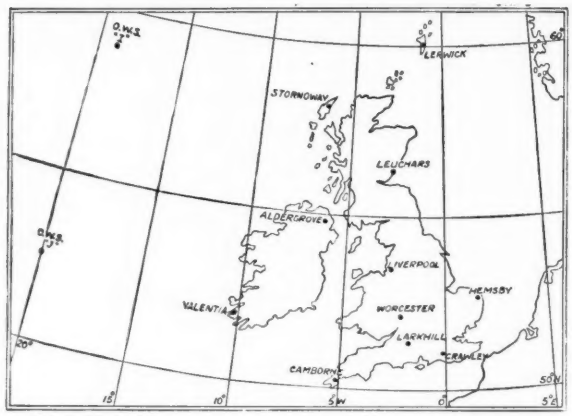

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FIGURE 7. Upper Air Stations: Great Britain, Ireland and Ocean Weather Ships.

present time to explain the possible cause of such turbulence.

(*vi*) Our knowledge of clear air turbulence is still very incomplete and much work needs to be done before we can answer the following vital questions:—

(*a*) What is the mechanical structure of the eddies causing the severe bumps and what is the nature of the stresses imposed on an aircraft flying through such turbulence?

Although the motion of the atmospheric particles seems to have a wave-like form in a vertical plane there is evidence that large horizontal forces are present. Theoretically, horizontal gusts would need to be extremely violent to have any appreciable effect on a fast moving aircraft but, from a meteorological point of view, their existence is somewhat easier to justify than vertical gusts.

(*b*) What is the probable maximum severity of clear air turbulence and how can "severity" be best computed? *e.g.* does the concept of "equivalent gust velocity" give a satisfactory indication of the stresses imposed on aircraft?

(*c*) What is the cause of severe clear air turbulence and how, either by notification from the ground or by instrumental observations in the air, or both, can a pilot receive adequate warning of its likely location?

(*vii*) There is a continued need for the co-operation of all pilots engaged in high altitude flying to supply information as detailed as possible on clear air turbulence encountered during flight, especially in the more severe cases.

Acknowledgments

The author is indebted to the Director of the Meteorological Office and the Controller, H.M. Stationery Office, for permission to reproduce certain charts and data from the Daily Aerological Record. He also wishes to thank the Director, Royal Aircraft Establishment, for supplying data on gusts recorded by counting accelerometers in Comet aircraft and Short Brothers and Harland Limited for supplying reports of high altitude turbulence experienced during test flights.

He acknowledges permission to publish the paper from the British Overseas Airways Corporation. Any opinions expressed in the paper are the author's and not necessarily those of the Corporation.

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TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

The Effect of Mean Stress on the Fatigue Strength of Magnesium Alloy ZW2

by

A. C. LOW, B.A.

(Mechanics and Materials Division, Mechanical Engineering Research Laboratory, Glasgow)

THE WORK reported in this Note originally formed part of a comprehensive investigation into the fatigue strength of magnesium alloy ZW2 (2 per cent. zinc, 0·65 per cent. zirconium) in sheet form. The major portion of the programme was eventually cancelled but the tests herein described are sufficiently self-contained to be reported by themselves. Direct stress fatigue determinations were made on small round test pieces machined from ¾ in. thick plate, at mean stresses of 0, 4,000, 8,000 and 13,000 lb./in.². Static and rotating bar fatigue tests were also made.

The conclusions reached were that the fatigue strength is continuously affected by tensile mean stresses. Within the limits of mean stress of zero and 13,000 lb./in.² and endurances of 10^5 and 10^8 cycles the mean fatigue behaviour may be expressed by mathematical equations and smooth curves of the constants in those equations.

1. MATERIAL

The material was supplied in the form of a 6 ft. × 3 ft. × ¾ in. sheet of magnesium alloy ZW2 (2 per cent. zinc, 0·65 per cent. zirconium). This was stated to have been hot-rolled from an extruded slab.

2. PROGRAMME AND METHOD OF TEST

Extensometer tensile, impact and hardness tests were made to determine the physical properties of the material. Tensile test pieces were 0·357 in. in diameter and were tested in an hydraulic testing machine of 10 tons capacity using an N.P.L. type extensometer. Standard 3 notch Izod impact test pieces were tested in an 120 ft.lb. Izod impact testing machine and Vickers hardness tests were made on a section through the plate.

Rotating bending fatigue tests on test pieces of the form shown in Fig. 1(*a*) were made in an N.P.L. two point loading machine running at about 3,000 r.p.m. and an *S-N* curve determined up to endurances of 5×10^8 cycles.

Direct stress fatigue tests on test pieces of the form shown in Fig. 1(*b*) were made in a Haigh machine of 1½ tons capacity running at 6,000 cycles per minute. *S-N* curves were determined up to endurances of 10^8 cycles at mean stresses of 0, 4,000, 8,000 and 13,000 lb./in.². (These values were dictated by the needs of a particular project.)

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The axis of each test piece was parallel to the principal direction of rolling of the sheet.

3. RESULTS OF TESTS

The results of the static tests are given in Tables I to III, and those of the fatigue tests in Tables IV and V, and Figs. 2 to 4.

4. DISCUSSION OF RESULTS

In Fig. 2 are plotted the results of the rotating bending fatigue tests and the direct stress fatigue tests at zero mean stress. The material is shown in the tensile tests (Table I) to have a very low limit of proportionality and a curving stress-strain curve beyond it. This probably accounts for most of the discrepancy between these two curves, nominal extreme fibre stress in the rotating bar tests being somewhat higher than the true stress due to the departure of the stress-strain curve from linearity.

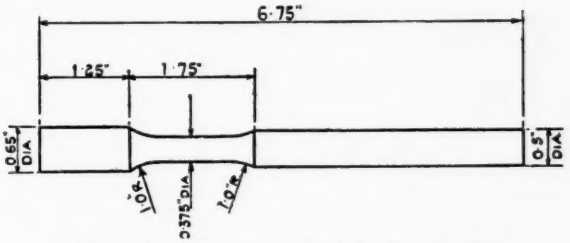

FIGURE 1(*a*). Dimensions of rotating bar test piece.

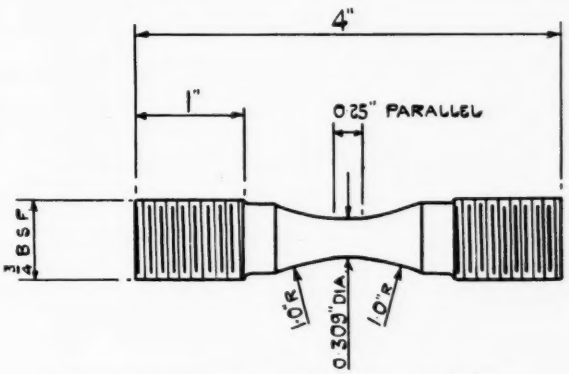

FIGURE 1(*b*). Dimensions of direct stress test piece.

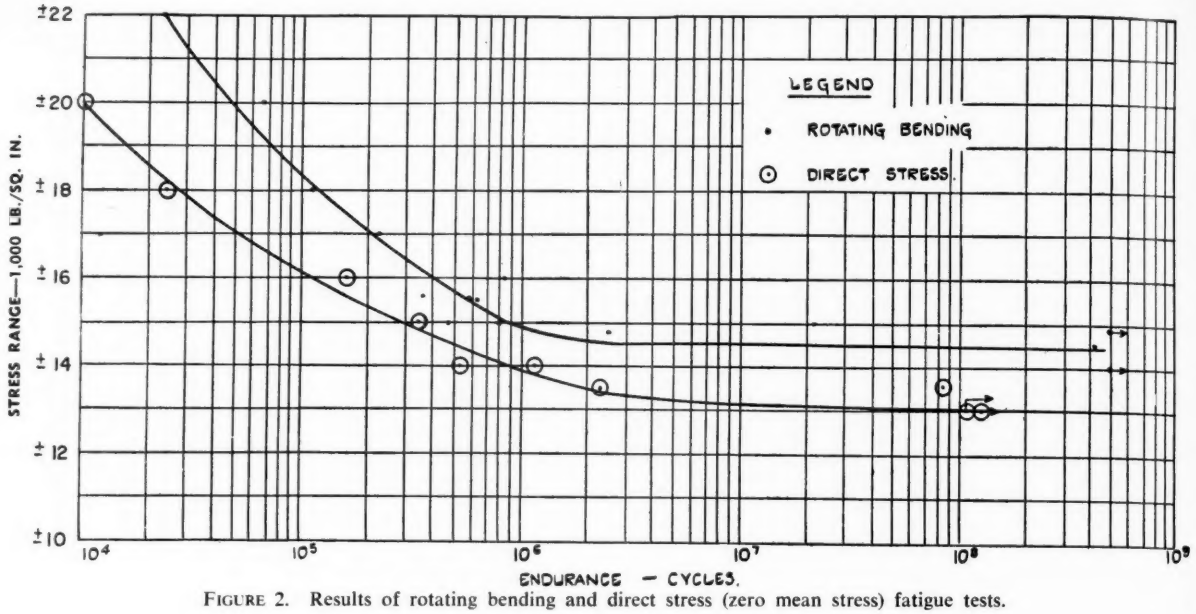

FIGURE 2. Results of rotating bending and direct stress (zero mean stress) fatigue tests.

In Fig. 3 are plotted the results of the direct stress fatigue tests at various mean stress levels. Despite the scatter of results shown, a reasonable family of mean curves may be drawn.

In Fig. 4 these curves are replotted in the form of constant life curves, showing the range and maximum stress of the cycle plotted against the mean stress for various endurances from 10^5 to 10^8 cycles. With the exception of one point on the 10^5 cycle curves the plotted points for each curve lie closely on a parabola whose equation may be expressed in the form:

$$(x+a)^2 = K(y+b)$$

where x = mean stress

y = maximum stress or stress range.

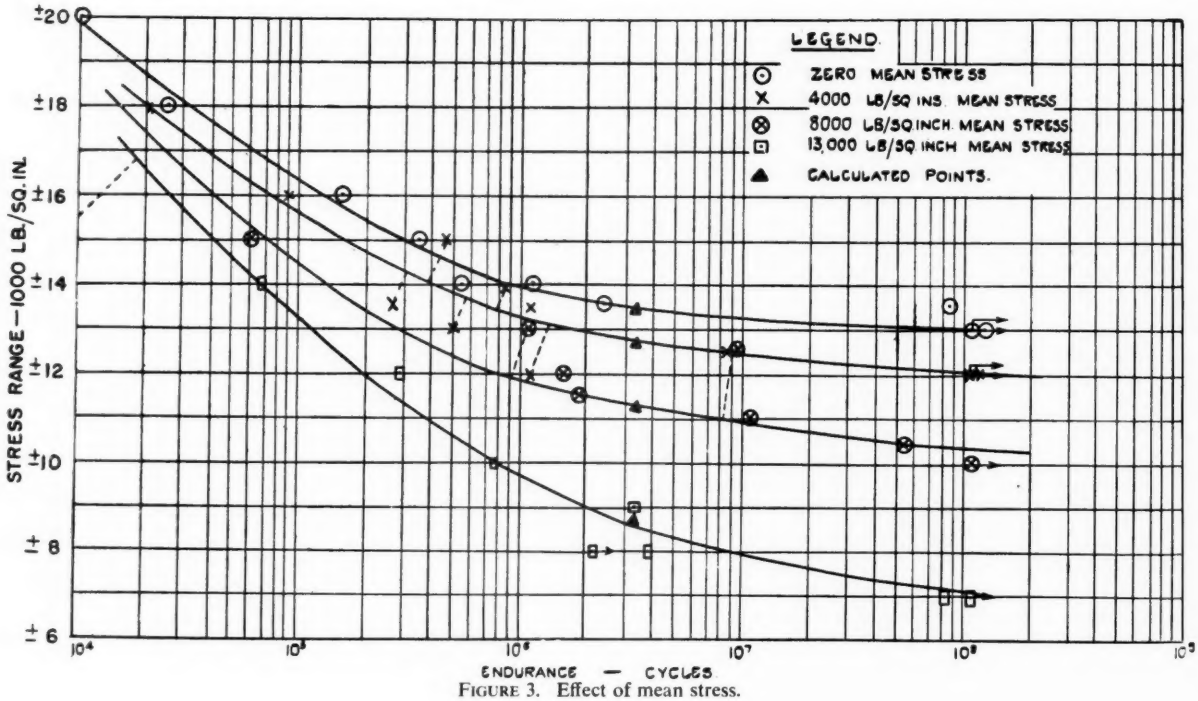

FIGURE 3. Effect of mean stress.

TABLE I

RESULTS OF TENSILE TESTS ON TEST PIECES OF MAGNESIUM ALLOY ZW2

Test mark	TFT 1B1	TFT 2B1	TFT 3C1
Diam. of test piece, in.	0·355	0·357	0·355
Estimated limit of proportionality, lb./in.²	—	4,500	5,500
0·1 per cent. proof stress, lb./in.²	19,000	19,500	20,500
0·2 per cent. proof stress, lb./in.²	22,700	22,700	23,300
Tensile strength, lb./in.²	37,600	37,400	37,400
Elongation on 1·26 in., (4 $\sqrt{}$area) per cent.	—	12½	11
Reduction of area, per cent.	11½	11½	9
Modulus of elasticity, lb./in.²	—	$6{\cdot}8\times10^6$	$6{\cdot}3\times10^6$

Each fracture was of the double shear type along shear planes at about 45° to the original faces of the plate (*i.e.* one fractured surface had the appearance of a chisel edge).

TABLE II

RESULTS OF IZOD IMPACT TESTS ON TEST PIECES OF MAGNESIUM ALLOY ZW2

10×10 mm. 3 notch test pieces to B.S.131.
Air temperature 13·1°C.

Test mark	*Energy absorbed, ft. lb.*			*Remarks*
	1st notch	*2nd notch*	*3rd notch*	
TFT 1B3	3	5½	3	1st and 3rd notches perpendicular to face of plate
1B4	5½	3	5	1st and 3rd notches parallel to face of plate
1B5	5½	3	5	

All fractures were of a fibrous appearance exhibiting a distinctly laminated formation parallel to the face of the plate. In some, where the notches were parallel to the face of the plate, the fracture was very ragged, layers having pulled out unevenly.

TABLE IV

RESULTS OF ROTATING BENDING FATIGUE TESTS ON TEST PIECES OF MAGNESIUM ALLOY ZW2

Test mark	*Nominal applied stress lb./in.²*	*Number of cycles Millions*
TFT 4A8	±22,000	0·023 B
3	±20,000	0·069 B
1	±18,000	0·108 B
9	±17,000	0·236 B
5	±16,000	0·846 B
10	±15,500	0·388 B
11	±15,500	0·596 B
15	±15,500	0·616 B
16	±15,000	0·495 B
13	±15,000	0·802 B
6	±15,000	21·400 B
17	±14,750	2·788 B
18	±14,750	506·963 U
14	±14,500	429·146 B
2	±14,000	503·600 U

B = Broken U = Unbroken

TABLE III

RESULTS OF VICKERS HARDNESS TESTS ON A CROSS SECTION OF PLATE OF MAGNESIUM ALLOY ZW2

Distance of impression from edge of plate mm.	*Hardness number* Hv_{10}
2½	67
4	67
5½	66
7	64
8½	63
10	62
11½	63
13	66
14½	67
16	65

The thickness of the plate was about 18½ mm. The hardness numbers have been approximated to the nearest unit.

TABLE V

RESULTS OF DIRECT STRESS FATIGUE TESTS ON TEST PIECES OF MAGNESIUM ALLOY ZW2

Test mark	*Applied stress lb./in.²*	*Number of cycles Millions*
TFT 4B5	0±20,000	0·010 B
4B6	0±18,000	0·027 B
4B7	0±16,000	0·160 B
4B8	0±15,000	0·359 B
4B11	0±14,000	0·533 B
4B9	0±14,000	1·134 B
4B12	0±13,500	2·502 B
4B10	0±13,500	98·884 B
4B13	0±13,000	100·907 U
4B14	0±13,000	108·897 U
4B16	4,000±18,000	0·021 B
4B17	4,000±16,000	0·090 B
4B18	4,000±15,000	0·461 B
4B15	4,000±14,000	0·876 B
4B19	4,000±13,500	0·288 B
2B3	4,000±13,500	1·050 B
2B4	4,000±13,000	0·503 B
2B6	4,000±12,500	8·610 B
2B7	4,000±12,000	1·099 B
2B5	4,000±12,000	106·547 U
2C1	4,000±12,000	103·400 U
2C2	8,000±15,000	0·061 B
2C3	8,000±13,000	1·180 B
2C4	8,000±12,500	8·530 B
2C5	8,000±12,000	1·674 B
2C6	8,000±11,500	1·963 B
2C7	8,000±11,000	10·244 B
2C8	8,000±10,500	56·255 B
3C3	8,000±10,000	101·104 U
3B4	13,000±15,000	0·007 B
3B2	13,000±14,000	0·068 B
3B1	13,000±12,000	0·299 B
3B3	13,000±11,000	5·656 B
3B5	13,000±10,000	0·792 B
3B6	13,000± 9,000	3·303 B
3B7	13,000± 8,000	2·072 U
3B8	13,000± 8,000	3·938 B
3C6	13,000± 7,500	0·117 B
3C5	13,000± 7,000	90·130 B
3C7	13,000± 7,000	106·525 U

B = Broken U = Unbroken in test portion

The values of the constants obtained are given in Table VI.

If the values of these constants are plotted against $\log_{10} N$, smooth curves may be drawn through the points, although it was not found possible to fit consistent mathematical curves to them.

TABLE VI

CONSTANTS IN EQUATIONS FOR CONSTANT LIFE CURVES

Life	*K*	*a*	*b*
Maximum stress			
10^5	−87·2	−40·1	−34·7
10^6	−54·8	−25·3	−25·6
10^7	−42·5	−19·0	−21·7
10^8	−39·1	−17·1	−20·5
Stress range			
10^5	−41·5	3·19	−32·7
10^6	−26·5	1·98	−28·0
10^7	−20·1	1·78	−26·5
10^8	−20·0	2·50	−26·2

If values of K, a and b are taken from these curves for a life of 3·163 million cycles ($\log_{10} 3{\cdot}163 = 0{\cdot}5$) the four points shown in Fig. 2 as calculated points are obtained, showing good agreement with the curves originally drawn.

CONCLUSION

Within the limits of mean stress of 0 and +13,000 lb./in.^{2} and limits of endurance of 10^5 to 10^8 cycles the mean behaviour of magnesium alloy ZW2 may be specified by mathematical equations and curves of the constants to these equations.

The stress range for any given life is continuously affected by mean stress, falling from ±13,000 lb./in.^{2} at zero mean stress to ±7,000 lb./in.^{2} at 13,000 lb./in.^{2} mean stress for a life of 100 million cycles.

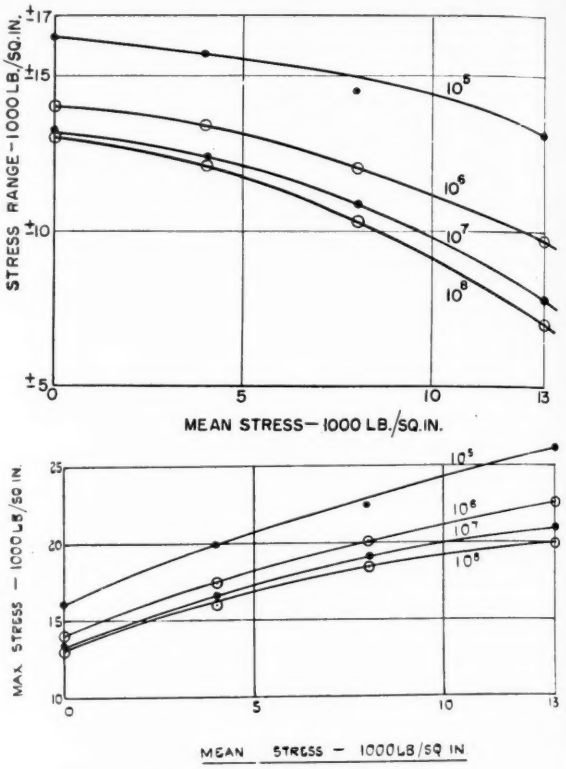

FIGURE 4. "Constant life" curves.

ACKNOWLEDGMENT

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Note on the Bending of a Circular Plate under Continuous Non-Normal Loading

by

K. I. McKENZIE and M. ROTHMAN

(The Northern Polytechnic, Holloway, N.7)

IN A PREVIOUS note[1] the authors gave a method of solution for the problem of a finite rectangular plate under non-normal loading. The problems considered in the present note are those of constant and variable inclined loading on a circular plate.

1. THE DIFFERENTIAL EQUATION

Consider a small element of area $r\,d\theta\,dr$. Let M_r, $M_{r\theta}$, Q_r and R be respectively the bending and twisting moments per unit length, the vertical shearing force per unit length and the horizontal force per unit length acting on the edge r=constant. Let M_θ, $M_{\theta r}$, Q_θ and Θ be the corresponding quantities acting on the edge θ=constant. Let F be the load per unit area with components P along the radius $\theta=0$ and Q vertically downward, and let S_α be the horizontal reaction per unit length on the edge of the plate $\theta=\alpha-\pi$.

Taking moments for the element about directions parallel and perpendicular to Or:

$$\left.\begin{aligned} \frac{1}{r}\frac{\partial M_\theta}{\partial\theta}+\frac{1}{r}(M_{\theta r}-M_{r\theta})-\frac{\partial M_{r\theta}}{\partial r}-\frac{\Theta}{r}\frac{\partial w}{\partial\theta}-Q_\theta=0 \\ \frac{\partial M_r}{\partial r}+\frac{1}{r}(M_r-M_\theta)+\frac{1}{r}\frac{\partial M_{\theta r}}{\partial\theta}-R\frac{\partial w}{\partial r}-Q_r=0 \end{aligned}\right\} \quad (1)$$

and equating the total shearing forces on the edges of the element to the downward load on it:

$$\frac{1}{r}Q_r+\frac{\partial Q_r}{\partial r}+\frac{1}{r}\frac{\partial Q_\theta}{\partial\theta}+Q=0. \quad (2)$$

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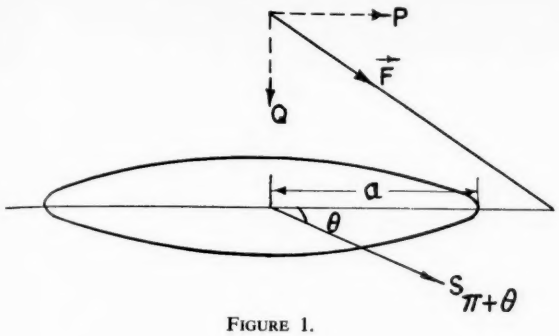

FIGURE 1.

Now the bending and twisting moments in polar co-ordinates are given by

$$M_r = -D\left[\frac{\partial^2 w}{\partial r^2} + \nu\left(\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right)\right];$$

$$M_\theta = -D\left[\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{\partial r}\frac{\partial^2 w}{\partial \theta^2} + \nu\frac{\partial^2 w}{\partial r^2}\right];$$

$$M_{r\theta} = D(1-\nu)\left[\frac{1}{r}\frac{\partial^2 w}{\partial r\,\partial\theta} - \frac{1}{r^2}\frac{\partial w}{\partial \theta}\right] = -M_{\theta r}$$

where D is the plate modulus and w the downward deflection of the plate, so that eliminating Q_r and Q_θ from (1) and (2), and substituting for M_r, M_θ, $M_{r\theta}$, $M_{\theta r}$, the differential equation of the deflection of the plate is given by:

$$\nabla_1^4 w = \frac{1}{D}\left[Q - \frac{1}{r}\frac{\partial}{\partial r}\left(rR\frac{\partial w}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial\theta}\left(\Theta\frac{\partial w}{\partial\theta}\right)\right]. \quad (3)$$

2. THE CASE OF CONSTANT LOADING

The partial differential equation (3) does not admit of a complete solution; however, by considering θ to be constant ($=\alpha$), a total differential equation in r is obtained for the deflection along the radius $\theta=\alpha$.

In this case equation (3) reduces to

$$\nabla_1^4 w = \frac{Q}{D} - \frac{1}{rD}\frac{d}{dr}\left(rR\frac{dw}{dr}\right) \quad . \quad . \quad (4)$$

and from Fig. 6 we have

$$R = -P(a+r)\cos\alpha + S_\alpha$$

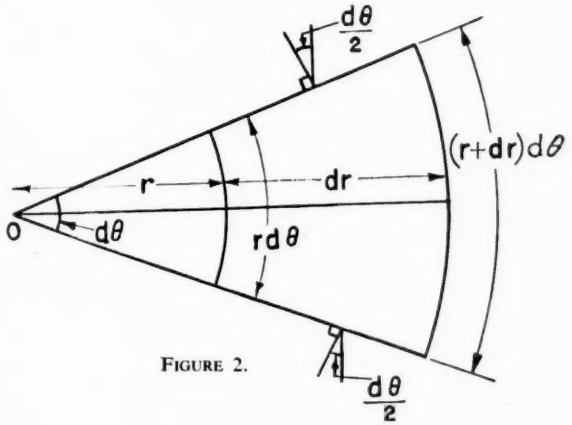

FIGURE 2.

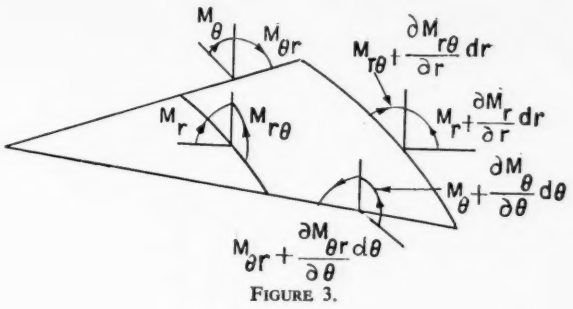

FIGURE 3.

so that (4) becomes

$$\nabla_1^4 w = \frac{Q}{D} + \frac{(Pa\cos\alpha - S_\alpha)}{D}\left(\frac{d^2w}{dr^2} + \frac{1}{r}\frac{dw}{dr}\right) + \frac{P\cos\alpha}{D}\left(r\frac{d^2w}{dr^2} + 2\frac{dw}{dr}\right). \quad . \quad (5)$$

If we now substitute

$$w = \sum_0^\infty B_{n,\alpha} r^n$$

in this equation we have

$$\sum_3^\infty n^2(n-2)^2 B_{n,\alpha} r^{n-4} + \frac{B_{1,\alpha}}{r^3} = \frac{Q}{D} + \frac{(Pa\cos\alpha - S_\alpha)}{D}\left(\frac{B_{1,\alpha}}{r} + \sum_2^\infty n^2 B_{n,\alpha} r^{n-2}\right) + \frac{P\cos\alpha}{D} 2B_{1,\alpha} + \sum_2^\infty n(n+1) B_{n,\alpha} r^{n-1}. \quad (6)$$

and equating the various coefficients:

$$\left.\begin{aligned} &B_{1,\alpha}=0,\ B_{3,\alpha}=0,\ B_{4,\alpha} = \frac{Q}{64D} + \frac{(Pa\cos\alpha - S_\alpha)}{D}\frac{B_{2,\alpha}}{16} \\ &(n+4)^2(n+2)^2 B_{n+4,\alpha} = \frac{(Pa\cos\alpha - S_\alpha)}{D}(n+2)^2 B_{n+2,\alpha} + \\ &\quad + \frac{P\cos\alpha}{D}(n+1)(n+2) B_{n+1,\alpha}. \end{aligned}\right\}$$

. . . . . (7)

If P is made zero the loading becomes normal and the solution is readily found to reduce to that given by Timoshenko[2].

All the B's except $B_{0,\alpha}$ can be expressed in terms of $B_{2,\alpha}$ and S_α, and if we assume the plate to be clamped,

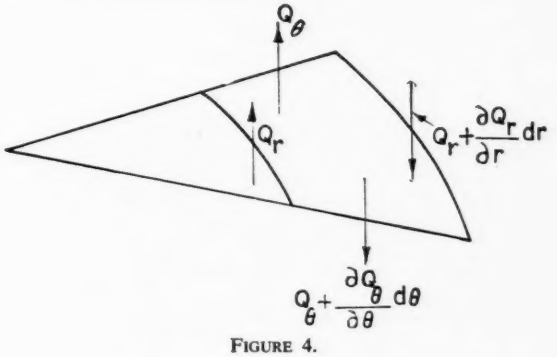

FIGURE 4.

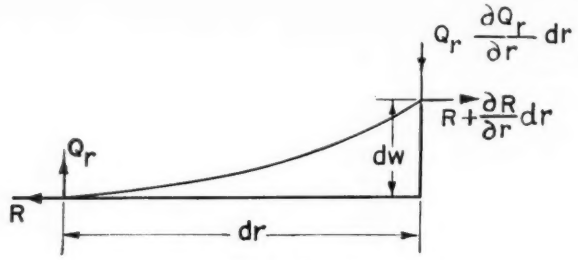

FIGURE 5(*a*).

we have the boundary conditions $w=0$ and $dw/dr=0$ on $r=a$, that is

$$\left.\begin{aligned} B_{0,\alpha}+B_{2,\alpha}a^2+\sum_4^\infty B_{n,\alpha}a^n&=0\\ 2B_{2,\alpha}a+\sum_4^\infty nB_{n,\alpha}a^{n-1}&=0\end{aligned}\right\} \quad . \qquad (8)$$

so that all the B's may be expressed in terms of S_α only.

Now the deflection of the centre of the plate w_0 must be the same irrespective of the direction $\theta=\alpha$ along which it is approached. Hence

$$w_0=B_{0,\alpha} \quad \text{for all } \alpha,$$

and in particular

$$B_{0,0}=B_{0,\pi} \qquad . \quad . \quad (9)$$

giving one relation between S_0 and S_π.

Also consideration of the equilibrium of an elementary strip taken along the diameter

$$\alpha=0, \quad \alpha=\pi$$

gives

$$S_0=S_\pi+2aP. \qquad . \quad . \quad . \quad (10)$$

We can thus solve for S_0, S_π, w_0 (and so $B_{0,\alpha}$ for α), and each $B_{n,\alpha}$ can be found explicitly, whence the problem is completely solved.

The case of a simply-supported plate can be solved in a similar manner, the second boundary condition in this case becoming

$$2B_{2,\alpha}+\Sigma\, n(n-1)B_{n,\alpha}a^{n-2}=0.$$

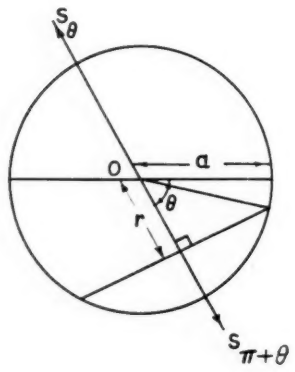

FIGURE 6.

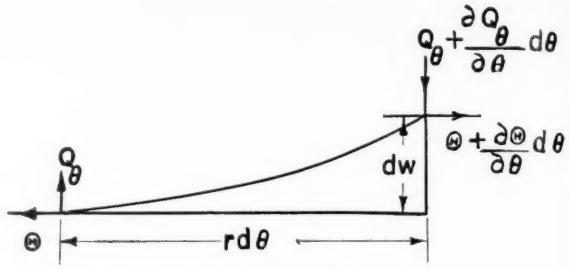

FIGURE 5(*b*).

3. THE CASE OF VARIABLE LOADING

Consider two cases of a continuously varying and inclined load over the plate.

Case 1

Assuming $P=pr^m$, $Q=qr^n$, where m and n are both positive integers, we have a load which is a maximum at the edge of the plate and decreases to zero at the centre.

We now have $R=pr^m(a+r)\cos\alpha+S_\alpha$ so that equation (4) gives:

$$\nabla_1^4 w=q\frac{r^n}{D}-\frac{S_\alpha}{D}\left(\frac{d^2w}{dr^2}+\frac{1}{r}\frac{dw}{dr}\right)+p\frac{a\cos\alpha r^m}{D}\left(\frac{d^2w}{dr^2}+\right.$$
$$\left.+\frac{m+1}{r}\frac{dw}{dr}\right)+p\frac{\cos\alpha r^{m+1}}{D}\left(\frac{d^2w}{dr^2}+\frac{m+2}{r}\frac{dw}{dr}\right) \quad (11)$$

for the deflection along the radius $\theta=\alpha$.

Again substituting

$$w=\sum_0^\infty B_{s,\alpha}r^s$$

we get

$$\sum_3^\infty s^2(s-2)^2B_{s,\alpha}r^{s-4}+\frac{B_{1,\alpha}}{r^3}$$
$$=\frac{qr^n}{D}-\frac{S_\alpha}{D}\left[\frac{B_{1,r}}{r}+\sum_2^\infty B_{s,\alpha}s^2r^{s-2}\right]$$
$$+\frac{pa\cos\alpha}{D}r^m\left[\frac{(m+1)B_{1,\alpha}}{r}+\sum_2^\infty s(s+m)B_{s,\alpha}r^{s-2}\right]$$
$$+\frac{p\cos\alpha}{D}r^{m+1}\left[\frac{(m+2)B_{1,\alpha}}{r}+\sum_2^\infty s(s+m+1)B_{s,\alpha}r^{s-2}\right].$$
$$. \quad . \quad . \qquad (12)$$

Now considering the case $m=n=1$ (other values of m and n may be similarly dealt with), and equating the various coefficients:

$$\left.\begin{aligned} B_{1,\alpha}=0=B_{3,\alpha};\ \ 16B_{4,\alpha}+\frac{S_\alpha}{D}B_{2,\alpha}&=0\\ 225B_{5,\alpha}-\frac{6Pa\cos\alpha}{D}B_{2,\alpha}&=\frac{q}{D}\\ (s+4)^2(s+2)B_{s+4,\alpha}+\frac{S_\alpha}{D}(s+2)B_{s+2,\alpha}-&\\ -\frac{Pa\cos\alpha}{D}(s+1)B_{s+1,\alpha}-\frac{P\cos\alpha}{D}SB_{s,\alpha}&=0\end{aligned}\right\}. \quad (13)$$

so that the various B's, except $B_{0,\alpha}$, can again be expressed in terms of $B_{2,\alpha}$ and S_α.

The boundary conditions are the same as for the case of constant loading, but the condition of equilibrium of the elementary diametral strip is

$$S_0 - \int_0^a pr\,dr = S_\pi + \int_0^a pr\,dr$$

or
$$S_0 = S_\pi + pa^2. \quad . \quad . \quad . \quad (14)$$

The deflection w can then be found along any radial arm $\theta = \alpha$ as before.

Case 2

Finally we take

$$P = p(r\cos\alpha + a);\quad Q = q(r\cos\alpha + a),$$

giving a distribution of loading which rises steadily from zero at one end of the diameter $\alpha = 0$, $\alpha = \pi$ to a maximum at the other end.

The differential equation is now

$$\nabla_1^4 w = \frac{q}{D}(r\cos\alpha + a) + \frac{(pa^2\cos\alpha - S_a)}{D}\left(\frac{d^2w}{dr^2} + \frac{1}{r}\frac{dw}{dr}\right) + \frac{p\cos^2\alpha}{D} r^2\left(\frac{d^2w}{dr^2} + \frac{3}{r}\frac{dw}{dr}\right) + \frac{pa\cos\alpha}{D}(1+\cos\alpha) r\left(\frac{d^2w}{dr^2} + \frac{2}{r}\frac{dw}{dr}\right). \quad (15)$$

and again substituting

$$w = \sum_0^\infty B_{n,\alpha} r^n$$

and equating the various coefficients, we have

$$\left.\begin{aligned} &B_{1,\alpha} = 0 = B_{3,\alpha};\quad 64\,B_{4,\alpha} = \frac{qa}{D} + \frac{(pa^2\cos\alpha - S_a)}{D}\,4\,B_{2,\alpha} \\ &225\,B_{5,\alpha} = \frac{q\cos\alpha}{D} + \frac{pa\cos\alpha}{D}(1+\cos\alpha)\,6\,B_{2,\alpha} \\ &(n+4)^2(n+2)\,B_{n+4,2} = \frac{(pa^2\cos\alpha - S_a)}{D}(n+2)\,B_{n+2,\alpha} + \\ &\quad + \frac{p\cos^2\alpha}{D} n B_{n,\alpha} + \frac{pa\cos\alpha}{D}(1+\cos\alpha)(n+1)\,B_{n+1,\alpha}. \end{aligned}\right\} \quad . \quad . \quad . \quad (16)$$

With the same boundary equations as in the previous examples, we have the equilibrium condition for the elementary diametral strip

$$S_0 - \int_0^a p(-r+a)\,dr = S_\pi + \int_0^a p(r+a)\,dr$$

or
$$S_0 = S_\pi + 2a^2 p. \quad . \quad . \quad (17)$$

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1. McKenzie, K. I. and Rothman, M. (1955). *Journal of the Royal Aeronautical Society*, T.N., p. 225, March 1955.
2. Timoshenko, S. (1940). *Theory of Plates and Shells*, p. 59, 1940.

Helicopter Stability in Hovering Flight

by

P. R. PAYNE

THE PRIMARY PURPOSE of this note is to draw attention to the powerful influence of Coriolis forces and flapping pin offset on helicopter stability. It is shown that, for a conventional rotor of small offset, the damping in pitch and the flight stability are greatly reduced by the absence of drag hinges, an effect which may explain the use of stabilising bars on the successful helicopters which use this configuration. A "see-saw" rotor without some form of synthetic damping would be very unpleasant to fly by present-day standards.

Offsetting the flapping hinges from the rotor centre has a powerful effect on damping however, and above a critical offset $\xi = 2a_0 h/R$ this effect becomes dominant. Equations are developed which give the effect of offset on the damping derivatives and it is shown that neither offset or drag hinges affect the period of the phugoidal oscillation. It is suggested that the use of offset to obtain suitable stability characteristics is preferable to the present trend towards auto-pilots, at least for small helicopters.

A secondary consideration in this note is the presentation of a simplified summary of those parameters which are of importance to the preliminary study of a project. The available literature seems unsuitable for project office use in that it either refers to untapered blades with the flapping hinges at the hub centre, or presents an exacting and fairly rigorous analysis of a form unsuitable for project study, and which is based, at the present state of the art, on inadequate assumptions. Familiarity with the basic principles of helicopter stability is assumed, as presented in Ref. 1 for example.

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NOTATION

(Dimensions are in accordance with the Perry system)

- a low speed lift curve slope = 5·73 (per radian)
- a_0 coning angle
- a_1 coefficient of Fourier series for flapping $= \cos\psi$
- b number of blades per rotor
- b_1 coefficient of Fourier series for flapping $= \sin\psi$
- c chord of blade at any station
- C_0 chord of blade at theoretical root (hub centre)
- C_{ML} coefficient of lift moment about flapping pin $= M_L/(\frac{1}{8}\rho V_T^2 R^2 abC_0)$
- C_{MG} coefficient of gyroscopic moment about flapping pin $= M_G/(\frac{1}{8}\rho V_T^2 R^2 aC_0)$

C_{MCF} coefficient of centrifugal force moment about flapping pin $= M_{CF}/(\frac{1}{8}\rho V_T^2 R^2 abC_0)$
C_T thrust coefficient $= T/(\frac{1}{8}\rho V_T^2 R^2 abC_0)$
(CF) centrifugal force $= \omega^2 M_m$
e flapping pin offset from hub centre
F a force
g acceleration due to gravity
h height between rotor hub and helicopter C.G.
I_F second moment of blade mass about the flapping pin
m mass
M_L lift moment about flapping pin
M_G moment of gyroscopic forces about flapping pin
M_{CF} moment of centrifugal forces about flapping pin
M_m first moment of blade mass about the flapping pin
M total moment about helicopter C.G.
M_Ω derivative of M with respect to Ω
M_V derivative of M with respect to V
P period time of oscillation
r radius of any element from the hub centre
R total blade radius
t^* blade taper $\left(1 - \frac{\text{tip chord}}{\text{root chord}}\right)$
t_n taper integral defined in Refs. 5 and 6
T_n taper integral defined in Ref. 6
U_P velocity component normal to the tip path plane
U_T velocity component in the tip path plane
V forward speed of helicopter
V_T rotor tip speed
$x = r/R$
α angle of attack of blade element
β flapping angle with respect to the no-feathering orbit
γ an inertia number $= I_F/(\frac{1}{8}\rho R^4 aC_0)$
δm elemental mass
ζ lag angle of blade on drag hinge
θ_R collective pitch angle at theoretical blade root
θ_T blade twist, root to tip (positive for "wash-out")
λ inflow ratio U_P/V_T
μ tip speed ratio V/V_T
$\xi = e/R$
ρ mass density of air
χ non-dimensional first moment of mass number $= M_m/(\frac{1}{8}\rho R^3 aC_0)$
ψ azimuth angle of blade
ω angular velocity of blade
Ω angular velocity of helicopter in pitch

BLADE LAG IN PITCH

If a helicopter is pitching with an angular velocity Ω, the vertical velocity at each blade element, due to the pitching, is $\Delta U\rho = \Omega r \cos\psi$ if we neglect the small in-plane velocities. Due to the freedom allowed by the flapping hinges the tip path plane lags behind the hub orbit by an angle a_1 so that when Ω is positive a_1 is negative.

In Ref. 2 Hohenemser has shown that coupling between flapping and feathering has a negligible effect on stability for practically attainable values (*i.e.* for values of δ_3 up to 40°). We therefore assume that the no-feathering and control orbits coincide, so that $\delta_3 = 0$, and consider velocity components relative to this plane.

Since the component of U_P due to flapping is

$$(r-e)\frac{d\beta}{dt}$$

we have, assuming

$$\beta = a_0 - a_1\cos\psi - b_1\sin\psi$$

$$\frac{d\beta}{dt} = \omega(a_1\sin\psi - b_1\cos\psi)$$

$$\frac{\Delta U_P}{V_T} = (x-\xi)(a_1\sin\psi - b_1\cos\psi) - x\frac{\Omega}{\omega}\cos\psi$$

The total change of angle of attack due to flapping and pitching is

$$\Delta\alpha = \Delta U_P/U_T = \frac{1}{x}(x-\xi)(a_1\sin\psi - b_1\cos\psi) - \frac{\Omega}{\omega}\cos\psi \quad . \quad . \quad . \quad (1)$$

The elemental lift on an element is

$$dL = \tfrac{1}{2}\rho U_T^2 a\Delta\alpha c\,dr.$$

and the elemental moment about the flapping pin

$$dM_L = \tfrac{1}{2}\rho V_T^2 x^2 (x-\xi)\,a\Delta\alpha C_0 (1-t^*x) R^2\,dx$$

defining $C_{ML} = M_L/(\frac{1}{8}\rho V_T^2 RaC_0)$ (per blade)

$$dC_{ML} = 4(1-t^*x)\alpha^2(x-\xi)\Delta\alpha dx$$

$$= 4(1-t^*x)\left[x(x-\xi)^2(a_1\sin\psi - b_1\cos\psi) - \right.$$

$$\left. - x^2(x-\xi)\frac{\Omega}{\omega}\cos\psi\right]$$

Integrating with respect to x as in Ref. 6

$$C_{ML} = (T_4 - \xi T_3)(a_1\sin\psi - b_1\cos\psi) - T_4\frac{\Omega}{\omega}\cos\psi \quad . \quad (2)$$

The moments about the flapping pin due to centrifugal, gyroscopic and inertia forces are all functions of flapping with respect to the hub orbit. From Ref. 6

$$C_{MCF} = (\gamma + \xi\chi)(a_0 - a_1\cos\psi - b_1\sin\psi) \quad . \quad (3)$$

The elemental gyroscopic force is

$$dF_G = 2\Omega\omega\delta m r\sin\psi.$$

The moment of this force about the flapping pin

$$dM_G = 2\Omega\omega\delta m\,r(r-e)\sin\psi$$

$$= 2\Omega\omega\delta m[(r-e)^2 + e(r-e)]\sin\psi$$

defining $C_{MG} = 2\Omega\omega[I + eMm]\sin\psi$

$M_G = M_L/(\frac{1}{8}\rho V_T^2 R^2 aC_0)$ (per blade)

$$C_{MG} = 2\frac{\Omega}{\omega}[\gamma + \xi\chi]\sin\psi \quad . \quad . \quad . \quad (4)$$

From Ref. 6 the equation for equilibrium about the flapping hinge is

$$\gamma\frac{d^2\beta}{dt^2} = C_{ML} - C_{MG} - C_{MCF} \quad . \quad . \quad (5)$$

$$\gamma(a_1\cos\psi + b_1\sin\psi) = (T_4 - \xi T_3)(a_1\sin\psi - b_1\cos\psi) -$$

$$- T_4\frac{\Omega}{\omega}\cos\psi - 2\frac{\Omega}{\omega}[\gamma + \xi\chi]\sin\psi -$$

$$- (a_0 - a_{1s}\cos\psi - b_{1s}\sin\psi)[\gamma + \xi\chi]$$

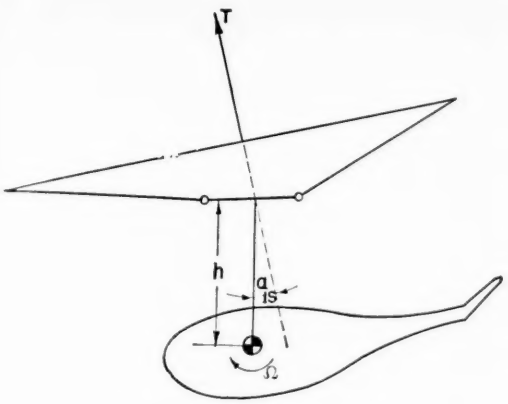

FIGURE 1. Damping in pitch.

Equating the $\cos\psi$ and $\sin\psi$ terms

$$(T_4-\xi T_3)\,b_1-T_4\frac{\Omega}{\omega}+a_1\xi\chi=0 \quad . \quad (6)$$

$$(T_4-\xi T_3)\,a_1-2\,(\gamma+\xi\chi)\frac{\Omega}{\omega}+b_1\xi\chi=0 \quad . \quad (7)$$

and from equation (7) since b_1 is very small

$$a_1=\frac{2\frac{\Omega}{\omega}(\gamma+\xi\chi)}{(T_4-\xi T_3)} \quad . \quad . \quad . \quad (8)$$

This result is general so long as the frequency of the helicopter oscillation is small compared with the rotor speed, and it can therefore be applied to all full-scale helicopters, where the period of oscillation is rarely less than 10 sec.

DAMPING IN PITCH

When a helicopter is pitching about its c.g. there are present a number of restraining forces which tend to damp the motion. The most important of these are due to the disc lag already analysed, and may be classified as three distinct components. The first is due to the inclination of the thrust vector, which may be taken as acting normal to the tip path plane at small tip speed ratios; this term is

$$-Tha_{1s}$$

From Ref. 7 there is a hub moment due to the forces transmitted to the hub by the blades, which for small values of μ and b_1 *is*

$$-\tfrac{1}{8}\rho V_T^2R^2baC_0\tfrac{1}{2}\xi\chi a_1=-\tfrac{1}{2}b\omega^2R\xi a_1M_{mF}.$$

Neglecting the small in-plane velocity at the hub caused by the pitching centre being at the c.g., the only other force is the in-plane Coriolis effect first described in Ref. 8, which results in a negative damping moment of

$$hb\omega^2M_ma_0a_1\,(1+d^2\zeta/dt^2)$$

the positive sign being due to the assumed sign convention. Since the Coriolis term is opposed to the other two, the total moment becomes

$$M=-a_1\,[Th+\tfrac{1}{2}b\omega^2M_mR\xi-bh\omega^2M_ma_0\,(1+d^2\zeta/dt^2)] \quad . \quad . \quad . \quad (9)$$

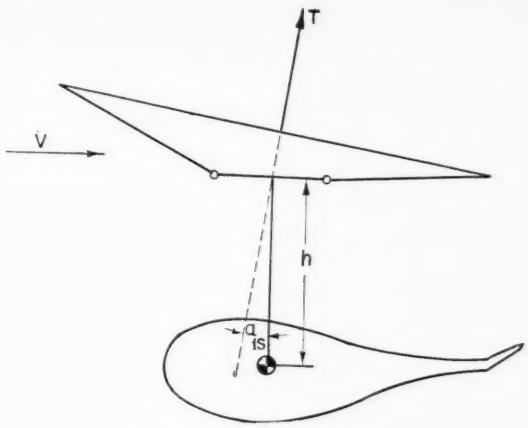

FIGURE 2. Flight stability.

When the angular velocity of the blade about the drag hinge is small compared with the rotational velocity, or zero, as in the case of a rotor without drag hinges, then the moment becomes

$$M=-a_1\,[h\,(T-b\omega^2M_ma_0)+\tfrac{1}{2}b\omega^2M_mR\xi].$$

$b\omega^2M_ma_0$ is of the same order as the rotor thrust, and indeed some authorities erroneously consider the two quantities to be identical. For a centrally located flapping hinge, when the two quantities most nearly approach one another, Ref. 5 gives the coning angle as

$$a_0=\frac{1}{\gamma}\,[t_4\theta_R-t_5\theta_T-t_3\lambda] \quad . \quad . \quad (10)$$

and the thrust coefficient as

$$C_T=T/(\tfrac{1}{8}\rho V_T^2RabC_0)=t_3\theta_R-t_4\theta_T-t_2\lambda \quad . \quad (11)$$

Therefore

$$\frac{T}{b\omega^2M_ma_0}=\frac{I_F\,(t_3\theta_R-t_4\theta_T-t_2\lambda)}{RM_m\,(t_4\theta_R-t_5\theta_T-t_3\lambda)}\simeq\frac{I_F}{0{\cdot}7\,RM_m} \quad (12)$$

Equations (10) to (12) are plotted in Fig. 3 for the rotor used as an example in this note, for zero flapping pin offset. It is evident that the rotor thrust is over 20 per cent. greater than the a_0 (CF) term, and that the ratio varies with collective pitch angle to some extent.

Since $(T-b\omega^2M_ma_0)$ is small compared with T, the damping in pitch of a helicopter without drag hinges is considerably smaller than a similar one with hinges, if the flapping pin offset is small. This may explain why all successful helicopters whose rotors have no drag hinges and zero flapping hinge offset possess some form of automatic stabilising device, such as the Bell or Hiller systems.

From equation (9) the derivative of damping in pitch is

$$M_\Omega=\frac{\partial a_1}{\partial\Omega}\left[Th+\omega^2M_mbR\left(\tfrac{1}{2}\xi-\frac{h}{R}\,a_0\,(1+d^2\zeta/dt^2)\right)\right] \quad (13)$$

and from equation (8)

$$\frac{\partial a_1}{\partial\Omega}=\frac{2\,(\gamma+\xi\chi)}{\omega\,(T_4-\xi T_3)} \quad . \quad . \quad . \quad (13a)$$

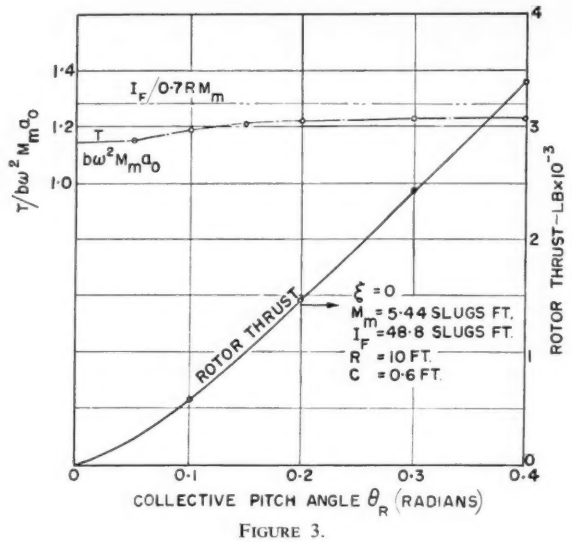

FIGURE 3.

An expression for the coning angle when ξ is finite can be obtained from equations (25) to (28) of Ref. 6 by neglecting μ^2 and other small terms

$$a_0 = \frac{T_4\theta_R - T_5\theta_T - T_3\lambda}{\gamma + \xi\chi} \quad . \quad . \quad (14)$$

FLIGHT STABILITY

If a hovering helicopter acquires horizontal velocity the tip path plane is tilted away from the direction of motion, applying a positive (nose-up) moment. This moment is a function of the flap-back angle a_1 as for the pitching moment, and therefore satisfies equation (9), while the derivative with respect to forward speed is

$$M_V = \frac{\partial a_1}{\partial V}\left[Th + \omega^2 M_m bR\left(\tfrac{1}{2}\xi - \frac{h}{R}a_0(1 + d^2\zeta/dt^2)\right)\right] \quad (15)$$

From Ref. 6 neglecting μ^2 and other small terms

$$a_1 = \frac{\mu(2T_3\theta_R - 2T_4\theta_T - T_2\lambda)}{(T_4 - T_5\xi)} \quad . \quad . \quad (16)$$

and the partial differential is

$$\frac{\partial a_1}{\partial V} = \frac{(2T_3\theta_R - 2T_4\theta_T - T_2\lambda)}{V_T(T_4 - T_5\xi)} \quad . \quad . \quad (17)$$

PERIOD OF OSCILLATION

It is not generally possible to make a single rotor helicopter stable in the sense that no phugoidal oscillation occurs after a disturbance. Miller in Ref. 3 has shown that even with a flapping hinge offset of $\xi = 0{\cdot}33$, the phugoid is still one of increasing amplitude, but it takes a long time to become twice the initial amplitude (21 sec. for Miller's example). The period of oscillation is therefore a convenient parameter in the study of stability characteristics, and in Ref. 2 Hohenemser has derived a simple equation for this, subject to a number of simplifying assumptions, one of which is that the fuselage inertia is zero.

$$P = \frac{2\pi}{\sqrt{g}}\sqrt{\frac{M_\Omega}{M_V}}\ (\text{sec.})$$

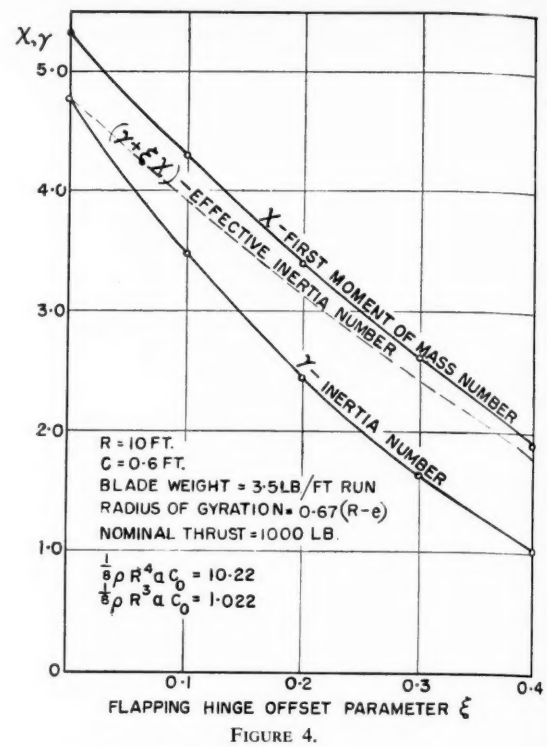
χ, γ
$(\gamma + \xi\chi)$ – EFFECTIVE INERTIA NUMBER
χ – FIRST MOMENT OF MASS NUMBER
γ – INERTIA NUMBER
R = 10 FT.
C = 0·6 FT.
BLADE WEIGHT = 3·5LB/FT RUN
RADIUS OF GYRATION = 0·67(R–e)
NOMINAL THRUST = 1000 LB.
$\frac{1}{8}\rho R^4 a C_0$ = 10·22
$\frac{1}{8}\rho R^3 a C_0$ = 1·022
FLAPPING HINGE OFFSET PARAMETER ξ

FIGURE 4.

Substituting equations (13) and (15)

$$P = \frac{2\pi}{\sqrt{g}}\sqrt{\frac{\partial a_1}{\partial\Omega}\Big/\frac{\partial a_1}{\partial V}} = \frac{2\pi}{\sqrt{g}}\sqrt{\frac{2(\gamma + \xi\chi)}{(2T_3\theta_R - 2T_4\theta_T - T_2\lambda)}} \quad . \quad . \quad . \quad . \quad (18)$$

Equation (18) leads to the surprising conclusion that the period of oscillation is unaffected by drag hinges, and in the rotor example which follows it is also shown to be independent of flapping hinge offset. A heavy blade tends to increase the period, and the use of tip-mounted engines is particularly beneficial from this point of view. The period also increases as the square root of blade radius, other things being equal, or roughly as the fourth root of all-up weight.

Although equation (18) is derived for zero fuselage moment of inertia the effect of a finite value is only to increase the period without modifying the general

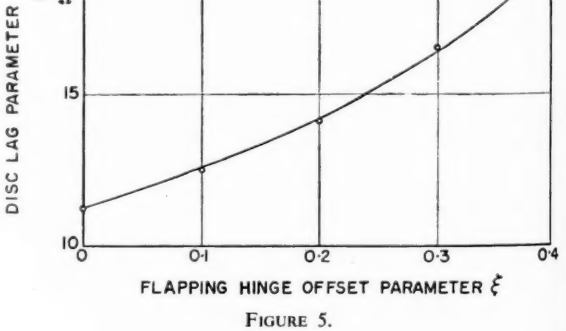

FIGURE 5.

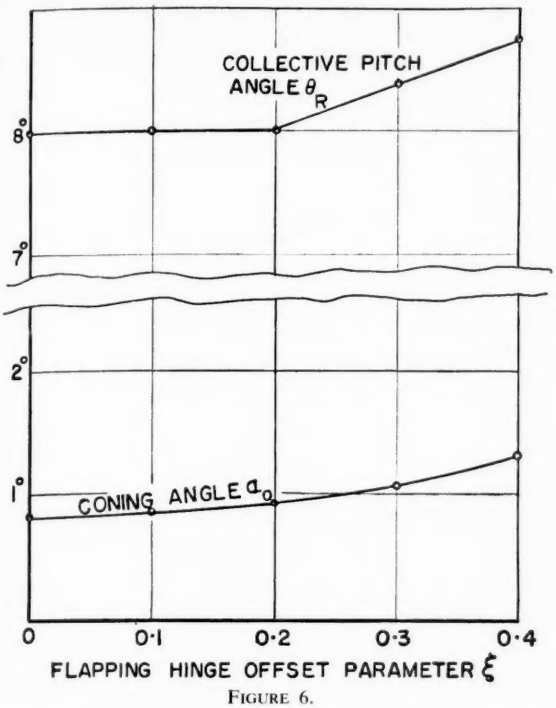

FIGURE 6.

trends. The nature of this increase cannot be calculated without considerable complication to the equations.

EXAMPLE ROTOR

In order to demonstrate the significance of the equations developed, calculations have been made for a 10 ft. radius untwisted rotor of constant chord with the characteristics specified in Figs. 3 and 4. For the purpose of an orthodox project analysis the total thrust of the rotor would be fixed, together with the main mass characteristics of the blades. Thus for increasing flapping pin offset the blade weight and mass moments about the flapping hinge will decrease in the manner shown by Fig. 4. From this variation the disc lag parameter $a_1\omega/\Omega$ is found from equation (8) and Fig. 5 shows that it increases steadily with increasing offset.

When the flapping hinge is outboard of $\xi=0{\cdot}2$ it reduces the available blade area so that the collective pitch needed to give a thrust of 1,000 lb. is correspondingly greater, the variation being as shown in Fig. 6. Moreover the reduction in second moment of mass of the blade about the hinge is only partly offset by the "effective inertia" component $\xi\chi$ (Fig. 4) so that the coning angle also increases with offset. The result is noteworthy in that it has been suggested in the past that flapping pin offset *reduces* the coning angle, a statement which is only true in the unrealistic case of γ being constant for variable ξ.

From equations (13*a*) and (17) the partial differentials $\partial a_1/\partial\Omega$ and $\partial a_1/\partial V$ are plotted against ξ in Fig. 7. The discontinuity in $\partial a_1/\partial V$ is due to the shape of the collective pitch angle curve in Fig. 6.

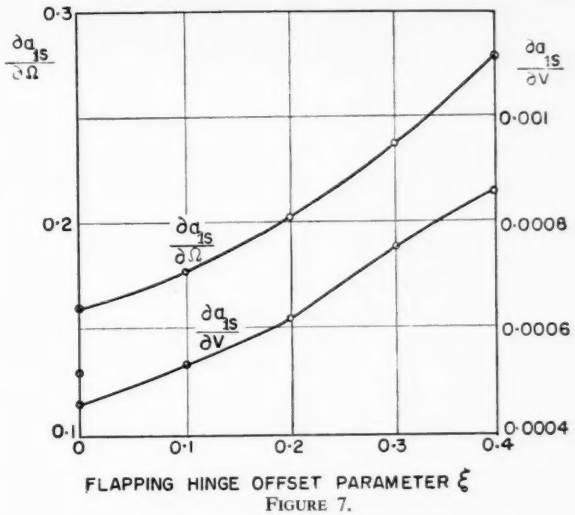

FIGURE 7.

Finally the damping derivatives and period of oscillation are plotted in Fig. 8 from equations (13), (15) and (18). While flapping pin offset and drag hinge restraint have no effect on the phugoidal period, they have considerable effect on damping and therefore on stability. For zero offset, which is common on contemporary helicopters, the use of drag hinges can increase the damping in both modes by nearly 300 per cent. A rotor without drag hinges, to have the same stability characteristics as one with "ideal" (zero offset) drag hinges, must have a flapping pin offset of

$$\xi=\frac{2a_0h}{R}. \quad . \quad . \quad . \quad (19)$$

—a value which is of the order of $\xi=0{\cdot}014$ for the example rotor. A larger helicopter, with a coning angle of 5° and $h/R=0{\cdot}3$ would require $\xi=0{\cdot}05$. It is suggested that equation (19) constitutes a good criterion for the design of rotors without drag hinges where minimum flapping pin offset is required.

For higher values of ξ the effect of offset becomes dominant, and a value $\xi=0{\cdot}2$ yields stability characteristics which are extremely good by present-day standards.

STABILITY OF HOVERING OSCILLATION

It is not at present possible to predict on purely theoretical grounds whether an oscillation will diverge or converge, because of ignorance as to the nature of the air flow through the rotor during an oscillation, but in Ref. 9 Sissingh has shown that instability (defined as a divergent oscillation) can be reduced by

(*a*) decreasing the moment of inertia of the fuselage
(*b*) increasing the damping in pitch
(*c*) increasing the height between the rotor hub and helicopter c.g.
(*d*) offsetting the flapping hinges from the hub centre.

Probably the most powerful of these is damping in pitch, and various devices such as the Bell stabilising bar are currently used to increase this term, particularly

on helicopters which do not use drag hinges. Fig. 7 makes it clear however that the use of offset flapping hinges enables the same or a larger increase in damping to be obtained, and on grounds of simplicity and reliability such a solution is to be preferred to a stabilising bar. In particular, the use of high offset hinges in conjunction with blades of high second moment of mass about the flapping pin (such as a rotor with tip-mounted engines) leads to a considerable improvement in stability characteristics.

GENERAL CONCLUSIONS

From considerations of rotor vibration, ground resonance and general mechanical complexity it can be said that the use of drag hinges on a helicopter rotor is not an attractive proposition, but for shaft-driven helicopters it is sometimes unavoidable for structural reasons. When tip-mounted engines are used the structural problems no longer arise and drag hinges are definitely precluded by the unmanageable first rotor vibration which would result from their use (Ref. 8). For mechanical reasons a see-saw rotor is therefore superficially attractive for use with tip-mounted engines. The theory of this note shows that such a configuration would be very unstable and difficult to fly unless some form of stabilising bar were used, constituting an unwelcome complication.

Helicopter stability in hovering is improved by the following design features:

(*a*) offsetting the flapping hinges from the hub centre.
(*b*) increasing the moment of inertia of the blade about the flapping pin.
(*c*) the presence of drag hinges.
(*d*) decreasing the moment of inertia of the fuselage.
(*e*) increasing the height between the rotor hub and the helicopter c.g.
(*f*) reducing the drag hinge offset.
(*g*) the use of a flexible hub.
(*h*) the use of a floating hub.
(*i*) reducing the coning angle.

In Ref. 3 Miller has shown that the following factors are also of importance.

(*j*) reducing the cyclic pitch variation imposed on the rotor due to the helicopter pitching, by means of a universal hub, thus increasing the damping in pitch. A tilting head cyclic control system approximates to this in the "stick free" case.
(*k*) the inclusion of a lead in the control system by means of a displacement gyro (Bell stabilising bar) or by offsetting the blade c.g. in front of the feathering or pitch-change axis. This enables the damping in pitch to be increased to any desired degree at the expense of control sensitivity.
(*l*) the use of a rigid feathering rotor to eliminate "flight stability" which is the primary cause of unstable oscillations.

Finally, it is suggested that the use of high offset flapping hinges is a more elegant and practical method of obtaining acceptable stability characteristics than the present trend to rate and attitude gyros, and auto-pilots, all of which add complication and weight to what is already a very complicated flying machine.

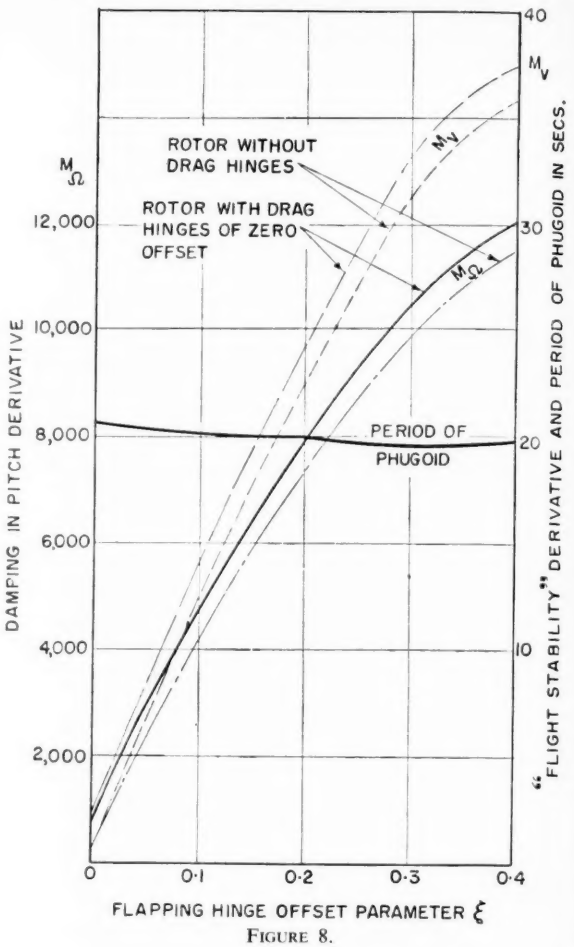

FIGURE 8.

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Reviews

GAS TURBINE PRINCIPLES AND PRACTICE. *Consulting Editor Sir Harold Roxbee Cox. George Newnes, London, 1955. 960 pp., diagrams. 90s.*

The publishers of the well-known engineering reference books have produced a significant contribution to the Gas Turbine literature in this weighty volume. There are 23 specialist authors* and 28 major sections. Despite the wide range there is a praiseworthy uniformity in the standard, which is generally clear and practical throughout.

Sir Harold Roxbee Cox contributes the Foreword and the Introduction. His leadership and imagination have done much for the present position of the Gas Turbine in this country.

The opening sections deal lucidly with the basic concepts of gas turbine cycles, thermodynamic processes, mechanical design of components and aerodynamic theory. Three interesting articles treat positive displacement compressors (*e.g.* the Lysholm) the piston gas generator (Napier Nomad) and the radial inflow turbine.

One of the larger sections (64 pages) deals with materials and contains much essential information attractively presented.

In the design of a gas turbine plant the estimation of the steady stresses is the first stage of the stressing process, and the description of some standard methods is a valuable feature of the book. The following section deals with vibration. The actual stresses can be estimated, if a full appreciation of the loads induced by vibration can be obtained.

Liquid and solid fuels are discussed at about equal length with their several aspects of operative properties, specifications and special problems. There is a little overlapping with the data under aircraft applications. A section on heat exchangers comprises a brief introduction to the principles of the subject, a well informed critical appraisal of leading design features and a useful collection of information on current heat exchangers.

The section on Aircraft Applications of some 120 pages, is compiled by R. H. Schlotel, Director of Industrial Gas Turbines, Ministry of Supply. It is well written and informative in the clear style of a responsible expert. One regret is that the material is limited to British practice.

Tabulated data on 52 gas turbine power plants and a number of diagrams illustrate stationary applications. Two sections are devoted to marine use—mercantile and naval. Technical achievements so far are far less certain than with the aircraft gas turbine owing to the long life requirement. One notable point of present British Naval practice is the apparent reluctance to accept the V.P. screw. Three sections deal in turn with applications of the gas turbine to road vehicles, locomotives and industrial processes. Some information is given on the major British projects but these are yet in the early stages of development.

The various sections each contain a useful bibliography. At the end of the book, along with a list of educational facilities, there is a complete index and some supporting tables.

There is much in this volume that will interest the engineering industries and the team of authors are to be congratulated on the results of their efforts.—A. W. MORLEY.

GAS TURBINES I: CYCLES AND PERFORMANCE ESTIMATION. *J. Hodge. Butterworth, London, 1955. 329 pp., diagrams. 50s.*

This volume is the first of a new series, under the general editorship of Mr. Hodge, which is devoted to various aspects of gas turbine technology. Apart from its own considerable merits, it whets the appetite for a series which, if it maintains this initial standard, should prove an invaluable acquisition to student or practising engineer alike (if he can afford it).

The object of the book is the exposition of the methods of design-point and off-design performance calculation for various forms of gas turbine, the provision of basic thermodynamic data to make this possible, and the presentation of design-point data for a large number of possible cases in graphical form.

The first chapter deals with definitions, basic data and general methods of calculation. This is particularly useful for the careful assessment it makes of the effect of using various mean specific heats in place of exact data. Since it is concluded that a single mean value is justifiable for compression and one of a series of values (related to the temperature) for expansion, it is difficult to understand why the author has devoted 55 pages of this 90-page chapter to reprinting *in extenso* from Fielding and Topp's N.G.T.E. report on gas properties, for while such a reprint is certainly needed (preferably as an R. & M. or A.R.C. Current Paper) the scale here used is too small and the curves are not used in the remainder of the book.

The second chapter deals with the analysis of some simple cycles in which all losses are assumed negligible except those in the compressor and turbine. This is followed by two chapters on shaft power engines and aircraft engines respectively, in which all losses are allowed for; in each case the corresponding ideal cycle is analysed for comparison.

The preparation of these three chapters must have involved a prodigious amount of calculation, for all results (design-point only) are presented for a wide range of temperatures, pressure ratios, efficiencies and ambient conditions. As regards the aircraft engine cycles, it is interesting to see the reheated turbo-jet and by-pass cycles and also the simple by-pass cycle, given due consideration. Time alone can tell whether all this effort has been worth while, but it would seem that the publication of a consistent set of data covering such a comprehensive range of conditions will be widely appreciated. If one may quibble, it is at times irritating to have to turn over a number of pages of graphs to find the end of the sentence one is reading: it might be worth considering whether in future editions the graphs could be grouped at the ends of the chapters.

A descriptive chapter on examples of applications—mainly industrial—then follows. This is only of general interest to the aero-engine specialist.

Finally, a reasonably long chapter is devoted to the all-important subject of off-design performance. Inevitably the content is less specific than in the earlier chapters, but

*The Specialist Authors are: I. G. Bowen, J. B. Bucher, A. D. S. Carter, L. J. Cheshire, C. G. Conway, L. G. Copestake, G. B. R. Fielden, J. R. Forshaw, E. Glaister, S. K. Hambling, R. I. Hodge, T. F. Hurley, A. W. H. Jamieson, C. S. King, H. Rowling, O. A. Saunders, R. H. Schlotel, J. Shapiro, A. G. Smith, G. F. A. Trewby, H. E. Upton, R. E. Wigg and P. H. W. Wolff.

sufficient information is given to enable the reader to handle any case he is likely to have to deal with.

One leaves this book with a feeling of gratitude that such a thorough treatment should have been undertaken, mingled with the impression that the cost could have been considerably reduced, and the potential market thereby increased, if the pruning-knife had been used fairly drastically. Apart from the redundant information in Chapter 1 already referred to, one feels that the author need not have underestimated the abilities of his readers to quite the extent he has in working out even the simplest algebraic processes at great length, leading to long passages of symbology of doubtful utility which must have caused consternation to the printer. One hastens to add that the standard of printing is extremely high: the only serious error is the omission of the term $\left(\frac{F}{\sqrt{T_0}}+\frac{V}{g\sqrt{T_0}}\right)^{-1}$ from the expression for $\frac{\partial F/\sqrt{T_0}}{\partial \Delta T_0/T_0}$ on page 127.—J. R. PALMER.

SERVOMECHANISM PRACTICE. *William R. Ahrendt. McGraw Hill, London, 1954. 349 pp. Illustrated.*

This is a book which gets right down to the hardware of servomechanisms. The reader is assumed to be familiar with the theory of the subject (which is however summarised concisely for reference in an Appendix), and attention is concentrated on practical details of the components—methods of manufacture, tolerances, accuracy, sources of error, working conditions.

An introductory chapter presents some of the main applications of servos, and the essential components which are common to all types. These components are then treated in detail.

The usual types of error detector are first discussed, and the distinctive characteristics of each of the diverse types of synchro are clearly set out and summarised in a table. The use of two-speed synchronising networks in reducing synchro error, and the associated problems which arise, receive special consideration. The chapter on passive networks contains another useful tabular summary, giving the transfer functions of a wide variety of networks.

Electronic amplifiers are treated in specific relation to servomechanisms; the reader is assumed to be acquainted with the general subject of amplifier design. Magnetic amplifiers and rotating amplifiers each receive a chapter, but transistor amplifiers are not included.

Hydraulic systems are very fairly treated, again with the emphasis on the practical aspect; for example, the relative merits of silicone oils and hydrocarbon oils are discussed.

There follows a logical method of designing servomechanisms, ending with a "reminder table" to ensure that no problem is overlooked. Other chapters cover the manufacture, adjustment, fault finding and testing of servos. Finally, the author applies the information set out in the book to the design of a specific instrument servochemanism, starting from a given specification. Some 140 problems enable the student to test his grasp of the subject, and a brief bibliography is given.

The book as a whole gives a workmanlike impression, though there is occasional evidence of careless thinking on the part of the author. It is not true, for example, that non-linear potentiometers are made by "winding on a mandrel which has the shape of the function." Nor can a smaller voltage possibly be equal to the square root of 2 times a larger voltage (p. 34).

Mildly irritating too is a tendency to spoon-feed the reader. However, for those who have studied the theory of servomechanisms but wish to know more about the actual components that make up a practical system, the book can be recommended.—S. J. GARVEY.

LE DROIT AERIEN. *R. Saint-Alary. Librairie Armand Colin, Paris, 1955. 220 pp. 250 fr. (In French).*

R. Saint-Alary, Professor of Law at Toulouse, has surveyed the essentials of Air Law in 220 small pages, and has produced a book which should be of equal interest to those employed in civil aviation and to students of law. The subject is of ever-growing interest, both from the theoretical and practical aspect and this review of it includes a short historical review and chapters on the legal aspects of aircraft, air space, landing grounds, air crew and staff insurance, and the relations between the air lines and their customers.

AIRCRAFT MAINTENANCE AND REPAIR. Revised Edition. *Northrop Aeronautical Institute. McGraw Hill, New York, 1955. 444 pp. Illustrated. 60s.*

This is the revised edition of the book reviewed in the February 1950 Journal. Nearly every chapter has had material added or changed to bring it up to date. The most extensive changes are in the chapters on Hydraulics, Brake Systems, Landing Gear, Riveting, Sheet Metal and Woodwork, still written in the same, easy to follow, manner which characterises the whole book. The high standard of production has been maintained although costs have obviously risen, since the price has increased while the number of pages remains the same.

Additions to the Library

Agard. COLLECTED PAPERS ON AVIATION MEDICINE (Agardograph 6). Butterworth. 1955.

Agard. ANTHROPOMETRY AND HUMAN ENGINEERING (Agardograph 5). Butterworth. 1955.

Crawford, A. E. ULTRASONIC ENGINEERING. Butterworth. 1955.

Cutler, A. E. ANALOGUE COMPUTERS IN AIRCREW TRAINING APPARATUS. (Reprint). B.I.R.E. 1954.

Dryden, H. L. (Chairman). TRANSONIC TESTING TECHNIQUES (Fairchild Paper F.F.12). A Symposium. I.A.S. 1954.

Gregory, N. *et al.* ON THE STABILITY OF THREE-DIMENSIONAL BOUNDARY LAYERS WITH APPLICATON TO THE FLOW DUE TO A ROTATING DISK. Royal Society. 1955.

Hewat, I. and W. A. Waterton. THE COMET RIDDLE. Muller. 1955.

Macmillan, N. GREAT AIRMEN. Bell. 1955.

Paterson, T. T. MORALE IN WAR AND WORK. Parrish. 1955.

Penner, S. S. CHEMICAL REACTIONS IN FLOW SYSTEMS (Agardograph 7). Butterworth. 1955.

Timoshenko, S. and D. H. Young. VIBRATION PROBLEMS IN ENGINEERING. (Third Edition). D. van Nostrand. 1955.

Wass, C. A. A. AN INTRODUCTION TO ELECTRONIC ANALOGUE COMPUTERS. Pergamon. 1955.

Wilson, E. E. WINGS OF THE DAWN. (A Study of Air Power as a Contribution to Civilization). Author. 1955.

Reports

AERODYNAMICS

Boundary Layer

Boundary-layer control for high lift by suction at the leading-edge of a 40 deg. swept-back wing. E. D. Poppleton. R. & M. 2897 (*October* 1951, *published* 1955).

Wind-tunnel tests have been made on a 40° sweptback wing, 10 per cent. thick with constant chord and an aspect ratio of 4·6. Boundary layer control was applied along the whole leading edge, and a comparison was made between the effects of distributed suction and suction through a slot. A 45 per cent. Fowler flap was used in some tests.—(1.1.5).

Méthode de calcul de la couche limite tridimensionnelle. Application a un corps fuselé incliné sur le vent. E. A. Eichelbrenner and A. Oudart. O.N.E.R.A. Publication No. 76 (1955).—(1.1.4.1).

A method of quadrature for calculation of the laminar and turbulent boundary layer in case of plane and rotationally symmetrical flow. E. Truckenbrodt. N.A.C.A. Technical Memorandum 1379 (*May* 1955).

For calculation of the characteristic parameters of the boundary layer (momentum-loss thickness and form parameter for the velocity profile), two quadrature formulas are given which are valid for the laminar as well as for the turbulent state of flow. These formulas cover both the two-dimensional and the rotationally symmetrical case.—(1.1.0).

Separation, stability, and other properties of compressible laminar boundary layer with pressure gradient and heat transfer. M. Morduchow and R. G. Grape. N.A.C.A., T.N. 3296 (*May* 1955).

A theoretical study is made of the effect of pressure gradient, wall temperature, and Mach number on laminar boundary-layer characteristics and, in particular, on the skin friction and heat transfer coefficients, on the separation point in an adverse pressure gradient, on the wall temperature required for complete stabilisation of the laminar boundary layer, and on the minimum critical Reynolds number for laminar stability. A simple and accurate method of locating the separation point in a compressible flow with heat transfer is developed.—(1.1.4).

Longitudinal turbulent spectrum survey of boundary layers in adverse pressure gradients. V. A. Sandborn and R. J. Slogar. N.A.C.A., T.N. 3453 (*May* 1955).

Results of measurements of the longitudinal velocity-component spectra at various positions through the boundary layer for four stations in increasing adverse pressure gradients are presented in tabular form. A comparison is presented between longitudinal turbulence spectra in zero pressure gradient and in moderate adverse pressure gradients.—(1.1.3.1).

Effect of a discontinuity on turbulent boundary-layer-thickness parameters with application to shock-induced separation. E. Reshotko and M. Tucker. N.A.C.A., T.N. 3454 (*May* 1955).

The problem of shock-induced turbulent boundary layer separation was analysed by an approximate method. This method is based on a moment-of-momentum equation and calculates the change of boundary layer thickness parameters and form factor caused by a discontinuity where effects of friction can be neglected. The form of the result suggests that the Mach number ratio across the shock is a characteristic parameter for defining shock induced separation. The method is also used to estimate the effects of mass transfer on the boundary layer thickness parameters for zero pressure gradient.—(1.1.3.4).

Compressible Flow

See also Wings and Aerofoils

A preliminary investigation of aerodynamic characteristics of small inclined air outlets at transonic Mach numbers. P. E. Dewey. N.A.C.A., T.N. 3442 (*May* 1955).

The aerodynamic characteristics of several outlets with inclined or curved axes discharging air into a transonic stream have been investigated. The data presented herein show the discharge coefficient of such outlets and the static-pressure distribution in the vicinity of the outlets for several values of stream Mach number and discharge flow parameter. Tuft observations, showing the vortex formation caused by the outlet discharge from a perpendicular and an inclined outlet, are also presented.—(1.2.2 × 1.5.1).

Internal Flow

See also Compressible Flow and Thermodynamics

An examination of the flow and pressure losses in blade rows of axial-flow turbines. D. G. Ainley and G. C. R. Mathieson. R. & M. 2891 (*March* 1951, *published* 1955).

Available information is studied and analysed to determine magnitudes of gas pressure losses and deflections in a wide variety of blade rows and also to determine the separate influences of blade shape, blade spacing, gas Mach number, Reynolds number, incidence, and so on. Of particular importance are the effects of secondary flows on the aerodynamic performance of a blade row and special attention is paid to "secondary losses," which form the difference between the total losses occurring in an actual turbine blade row and the smaller two-dimensional flow losses which are usually measured in a blade cascade tunnel. Effects of blade tip clearance are also studied.—(1.5.3).

Low-speed investigation of the effects of angle of attack on the pressure recovery of a circular nose inlet with several lip shapes. J. R. Blackaby. N.A.C.A., T.N. 3394 (*May* 1955).

An investigation was made at a free-stream Mach number of 0·237 of the effects of lip bluntness and profile on the total-pressure recovery of a circular nose inlet in a ducted body of revolution at angles of attack up to 25°.—(1.5.1).

Theoretical analysis of incompressible flow through a radial-inlet centrifugal impeller at various weight flows. I—Solution by a matrix method and comparison with an approximate method. V. D. Prian et al. N.A.C.A., T.N. 3448 (*June* 1955).

A method for the solution of the incompressible, non-viscous flow through a centrifugal impeller, including the inlet region, is presented. Several numerical solutions are obtained for four weight flows through an impeller at one operating speed. The results are presented in a series of figures showing stream lines and resultant velocity contours. A comparison is made with the results obtained by use of a rapid approximate method of analysis.—(1.5.2.2).

Theoretical analysis of incompressible flow through a radial-inlet centrifugal impeller at various weight flows. II—Solution in leading-edge region by relaxation methods. J. J. Kramer. N.A.C.A., T.N. 3449 (*June* 1955).

The detailed solution of the flow around the blade nose of a 48 in. diameter radial-inlet centrifugal impeller has been obtained by relaxation methods for four weight flows. The results are presented in a series of figures showing stream lines and relative velocity contours.—(1.5.2.2).

Estimation of inlet lip forces at subsonic and supersonic speeds. W. E. Moeckel. N.A.C.A., T.N. 3457 (*June* 1955).

The effects of inlet lip thickness on inlet performance are estimated as functions of mass flow for subsonic and supersonic flight speeds. At subsonic speeds, pressure-recovery

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

losses and additive drag are shown to decrease linearly with increasing lip frontal area if the maximum suction force is attained. At supersonic speeds, inlet drag increases linearly with inlet lip frontal area at full mass flow. For reduced mass flow, some reduction in additive drag is possible with lips of moderate thickness, but the magnitude of this reduction becomes negligible as flight speed increases.—(1.5.1).

LOADS

See also PROPELLERS

Theoretical and experimental investigation of the effect of tunnel walls on the forces on an oscillating airfoil in two-dimensional subsonic compressible flow. H. L. Runyan et al. N.A.C.A., T.N. 3416 (*June* 1955).

The integral equation defining the problem of an oscillating wing in a tunnel is treated and is presented in a form adapted to calculations. Application is made to a number of examples to illustrate the influence on the magnitude of wall effects of variations in frequency, Mach number, and ratio of tunnel height to wing semi-chord. Comparison is made with experimental measurements for several subsonic Mach numbers.—(1.6.3 × 1.10.1.1).

PERFORMANCE ESTIMATION

The ground run of aircraft in landing and take-off. M. A. Garbell. Garbell Aeronautical Series No. 3 (1951).—(1.7).

The initial en-route climb of aircraft. M. A. Garbell. Garbell Aeronautical Series No. 5 (1952).—(1.7).

The drift-down with partial power in air-carrier operation. M. A. Garbell. Garbell Aeronautical Series No. 7 (1953).—(1.7).

Optimum climbing techniques for high-performance aircraft. M. A. Garbell. Garbell Aeronautical Series No. 8 (1953).—(1.7).

Theoretical and experimental investigation of additive drag. M. Sibulkin. N.A.C.A. Report 1187 (1954).

The significance of additive drag is discussed and equations for determining its approximate value are derived. Charts show values of additive drag for open-nose inlets and for annular-nose inlets with conical flow at the inlet. The effects of variable inlet total-pressure recovery and static pressures on the centre body are investigated, and an analytical method of predicting the variation of pressure on the centre body with mass-flow ratio is given.—(1.7).

STABILITY AND CONTROL

See also TESTING AND INSTRUMENTS

Some calculations of the lateral response of two airplanes to atmospheric turbulence with relation to the lateral snaking problem. J. D. Bird. N.A.C.A., T.N. 3425 (*May* 1955).

Results of calculations of the lateral response to representative time histories of atmospheric turbulence for two aeroplanes having widely different dynamic properties indicate that, under the proper conditions, atmospheric turbulence can initiate and maintain a lateral hunting oscillation of an aeroplane, and that this oscillation can be fairly regular in both amplitude and frequency. This effect is more pronounced for lightly damped aeroplanes.—(1.8.1.1).

Theoretical investigation of a proportional-plus-flicker automatic pilot. E. C. Seaberg. N.A.C.A., T.N. 3427 (*May* 1955).

An analysis has been made of the stability of a supersonic canard airframe and a proportional-plus-flicker auto-pilot. The analysis consists of an investigation of the calculated transient responses based on the variation of the auto-pilot and aerodynamic parameters.—(1.8.2).

THERMO-AERODYNAMICS

Thermodynamische Zustandsgrossen und Stoffwerte fur Luft bei Dissoziationsgleichgewicht. H. J. Kaeppeler and H. G. L. Krause. Mitteilungen aus dem Forschungsinstitut fur Physik der Strahlantriebe E.V. No. 1 (*November* 1954).—(1.9.0 × 27.3).

Turbulent-heat-transfer measurements at a Mach number of 1.62. *M. J. Brevoort and B. Rashis. N.A.C.A., T.N.* 3461 (*June* 1955).

An axially symmetric annular nozzle was used to obtain essentially flat plate results for turbulent heat transfer coefficients and temperature-recovery factors. The test results are for a Mach number of 1·62 and for a Reynolds number range of $7{\cdot}22 \times 10^5$ to $1{\cdot}20 \times 10^8$.—(1.9.1).

WINGS AND AEROFOILS

See also LOADS AND AEROELASTICITY

The application of the exact method of aerofoil design. M. B. Glauert. R. & M. 2683 (*October* 1947, *published* 1955).

The design of aerofoils is considered in detail by Lighthill's exact method, in which the velocity over the aerofoil surface is prescribed as a function of the angular co-ordinate on the circle into which the aerofoil may be transformed. The mathematical basis of the method is set out, means for obtaining desired characteristics for the aerofoils are developed, and the procedure to be followed in the actual design is fully discussed.—(1.10.1.1).

Detailed observations made at high incidences and at high-subsonic Mach numbers on Goldstein 1442/1547 *aerofoil. H. H. Pearcey and M. E. Faber. R. & M.* 2849 (1954).

Detailed measurements, including surface-pressure distributions, shock-wave photographs and observations of boundary-layer separation, have been made over a wide range of incidence on the Goldstein 1442/1547 aerofoil NPL 177, previously tested at lower incidences.—(1.10.2.1).

Some applications of the Lamé function solutions of the linearised supersonic flow equations. Part I.—Finite swept-back wings with symmetrical sections and rounded leading edges. Part II. —Cambered and twisted wings. G. M. Roper. R. & M. 2865 (*August* 1951, *published* 1955).—(1.10.1.2).

Contribution à l'étude de l'aile portante en fluide compressible. R. Goethals and M. Menard. Publications Scientifiques et Techniques du Ministère de l'Air. No. 299 (1955).—(1.10.0.2).

Total lift and pitching moment on thin arrowhead wings oscillating in supersonic potential flow. H. J. Cunningham. N.A.C.A., T.N. 3433 (*May* 1955).

Total lift and moment coefficients are given for thin arrowhead wings oscillating in pitch and vertical translation which extend to the fifth power and to the third power of the frequency for the subsonic- and supersonic-leading-edge cases, respectively.—(1.10.1.2 × 2.0).

On the kernel function of the integral equation relating lift and downwash distributions of oscillating wings in supersonic flow. C. E. Watkins and J. H. Berman. N.A.C.A., T.N. 3438 (*May* 1955).

A suitable form of doublet potential that serves as a basis for deriving the kernel function for supersonic flow, corresponding to the kernel function for subsonic flow presented in N.A.C.A. T.N. 3131, is derived by using a cut-off or unit function. A treatment similar to that made for the subsonic kernel is made for the kernel function for supersonic flow. The singularities are isolated and discussed, and the kernel function is shown to lead to correct results for two-dimensional flow, and to reduce properly to the sonic case.—(1.10.1.2).

Hovering flight tests of a four-engine-transport vertical take-off airplane model utilizing a large flap and extensible vanes for redirecting the propeller slipstream. L. P. Tosti and E. E. Davenport. N.A.C.A., T.N. 3440 (*May* 1955).

The take-off, landing and hovering flight characteristics of a four engined transport, vertical take-off aeroplane with a remotely controlled free-flight model have been investigated. The model had four propellers distributed along the wing with thrust axes parallel to the fuselage axis. To produce direct lift for hovering flight the propeller slipstream was

deflected downward about 70° by a full-span 65 per cent. chord flap deflected 90° and eight extensible vanes arranged above the wing in a cascade relation.—(1.10.2.2 × 1.3.4).

Calculation of the supersonic pressure distribution on a single-curved tapered wing in regions not influenced by the root or tip. W. G. Vincenti and N. H. Fisher. N.A.C.A., T.N. 3499 (*June* 1955).

The shock-expansion method for the calculation of the pressures on cylindrical wings in supersonic flow is extended to tapered wings made up of single-curved surfaces. The method applies in regions where (*a*) the component of velocity normal to the surface rulings is supersonic and (*b*) the flow is not influenced by tips or junctures. In these regions the flow is defined by a pair of ordinary differential equations whose solution is readily obtained by numerical means. Results are shown and discussed for a representative triangular wing.—(1.10.1.2).

The calculation of pressure on slender airplanes in subsonic and supersonic flow. M. A. Heaslet and H. Lomax. N.A.C.A. Report 1185 (1954).

Under the assumption that a wing, body, or wing-body combination is slender or flying at near sonic velocity, expressions are given which permit the calculation of pressure in the immediate vicinity of the configuration. The disturbance field, in both subsonic and supersonic flight, is shown to consist of two-dimensional disturbance fields extending laterally and a longitudinal field that depends on the streamwise growth of cross-sectional area. A discussion is also given of couplings, between lifting and thickness effects, that necessarily arise as a result of the quadratic dependence of pressure on the induced velocity components.—(1.10.1.2 × 1.2.0).

Aerodynamic characteristics of several 6-percent-thick airfoils at angles of attack from 0° to 20° at high subsonic speeds. B. N. Daley and D. R. Lord. N.A.C.A., T.N. 3424 (*May* 1955).

Aerodynamic characteristics obtained from two-dimensional tests of eight 6 per cent. thick symmetrical aerofoils of the supersonic and subsonic type are presented at angles of attack from 0° to 20° and at Mach numbers from 0·3 to about 0·9.—(1.10.2.1).

The transonic characteristics of 38 cambered rectangular wings of varying aspect ratio and thickness as determined by the transonic-bump technique. W. H. Nelson and W. J. Krumm. N.A.C.A., T.N. 3502 (*June* 1955).

An investigation was made in the Ames 16 ft. high-speed wind tunnel utilising the transonic-bump technique to determine the aerodynamic characteristics at transonic Mach numbers of 38 cambered rectangular wings. The wings had aspect ratios of 4, 3, 2, 1·5 and 1, and N.A.C.A. 63A2XX and 63A4XX sections with thickness-to-chord ratios of 10, 8, 6, 4 and 2 per cent. The Mach number range was 0·6 to 1·12 with corresponding Reynolds numbers of 1·7 to 2·2 million. The data are presented without analysis.—(1.10.2.2).

Testing and Instruments

A technique utilizing rocket-propelled test vehicles for the measurement of the damping in roll of sting-mounted models and some initial results for delta and unswept tapered wings. W. M. Bland and C. A. Sandahl. N.A.C.A., T.N. 3314 (*May* 1955).

A free flight test technique with which the damping in roll of sting-mounted models can be measured over the high subsonic, transonic and supersonic speed range with rocket-propelled test vehicles is described. Initial results for delta and unswept tapered wings are presented and compared with theory.—(1.12.2 × 1.8.1).

Acoustical treatment for the N.A.C.A. 8- by 6-foot supersonic propulsion wind tunnel. L. L. Beranek et al. N.A.C.A., T.N. 3378 (*June* 1955).

The results are summarised of a project at the Lewis Flight Propulsion Laboratory to silence the 8- by 6-ft. supersonic wind tunnel. Sound measurements in the neighbourhood surrounding the tunnel were conducted to evaluate the noise attenuation requirements. A muffler development programme was continued until these attenuations were achieved. The final design for the acoustic treatment is described and experimental performance curves are compared with anticipated theoretical results.—(1.12.1.3).

Heat-loss characteristics of hot-wire anemometers at various densities in transonic and supersonic flow. W. G. Spangenberg. N.A.C.A., T.N. 3381 (*May* 1955).

An experimental investigation was made of the heat-loss characteristics of heated fine wires suitable for use as anemometers in turbulence research. Speeds ranged from low subsonic to Mach number 1·9. Density and temperature loading were varied over wide limits, and wire diameters ranged from 0·00005 to 0·0015 in.—(1.12.6.3).

AEROELASTICITY

See also Aerodynamics: Wings and Aerofoils

The flow around oscillating low aspect ratio wings at transonic speeds. M. T. Landahl. K.T.H. Aero. T.N. 40 (*June* 1954).

When certain conditions are fulfilled for thickness ratio, aspect ratio and reduced frequency for a three-dimensional wing, it can be shown that the partial differential equation for the non-steady perturbation potential can be reduced to a comparatively simple linear equation. The solution is then obtained by applying a Fourier transformation in the free-stream direction and then using an iterative process developed by Adams and Sears for steady flow. The method gives solutions valid for low combinations of aspect ratio and reduced frequency.—(2 × 1.10.1.2).

A dynamic-model study of the effect of added weights and other structural variations on the blade bending strains of an experimental two-blade jet-driven helicopter in hovering and forward flight. J. L. McCarty and G. W. Brooks. N.A.C.A., T.N. 3367 (*May* 1955).

The blades of an experimental two-blade jet-driven helicopter were subject to a condition of near resonance between the frequencies of the first elastic bending mode of the blades and the third harmonic component of the aerodynamic loading which resulted in high bending strains during normal flight conditions. An experimental investigation was conducted of a 1/10-scale in the design configuration on the blade bending strains.—(2).

AIRCRAFT OPERATION

L'assistenza al volo e la sicurezza della navigazione aerea in Europa. P. Magini. Centro Per Lo Sviluppo Dei Trasporti Aerei. No. 32 (*April* 1955).—(5.1.1).

Rapporti tra linee marittime e linee aeree. F. Manzitti. Centro Per Lo Sviluppo Dei Trasporti Aerei. No. 34 (*May* 1955).—(5.1.0).

Pianificazioni di economia dei trasporti e politica dei trasporti aerei. R. Trevisani. Centro Per Lo Sviluppo Dei Trasporti Aerei (*May* 1955).—(5.2).

Le role de l'aviation civile dans la civilisation moderne. E. Pepin. Centro Per Lo Sviluppo Dei Trasporti Aerei. (*May* 1955).—(5.1.0).

L'influenza dell' aviazione sul progresso della tecnica e degli altri mezzi di trasporto. A. Eula. Centro Per Lo Sviluppo Dei Trasporti Aerei (*May* 1955).—5.1.1).

AIRPORTS

Recent developments in visual low-approach and landing aids for aircraft. M. A. Garbell. Garbell Aeronautical Series No. 1 (1951).

This report discusses a new approach-light system, installed at major U.S. airports, which enables commercial airliners to operate down to a CAA-approved minimum 100 ft. ceiling and ¼ mile visibility.—(6.5).

A new system of surface markings for aircraft runways. M. A. Garbell. Garbell Aeronautical Series. No. 2 (1953).

Recent strides in the development of luminous approach and landing aids for aircraft have given rise to the need for a

surface marking system for aircraft runways that will enable the pilot to achieve consistently safe and gentle touchdowns in all visibility conditions. A novel surface marking system designed to meet this need is described.—(6.5).

The timing of airport traffic control as influenced by weather and aircraft performance. M. A. Garbell. Garbell Aeronautical Series. No. 4 (1951).

The present study was initiated by a need to determine the effect of the vagaries of weather on the acceptance rate of a crowded airport. The combined studies are focused on a "generalised" airport operated in accordance with present control practices and with present types of aircraft. This was necessary in order to analyse and understand the functioning of the present system of air traffic control first, from which to obtain a basis for a critical verification of such analysis, before attempting to predict the degree of susceptibility of future air-traffic-control systems to weather and to the anticipated performance characteristics of future aircraft.—(6.5 × 24).

The visual range in daylight, darkness, and twilight. M. A. Garbell. Garbell Aeronautical Series. No. 6 (1952).

Formulae, references and charts necessary for the calculation of the visual range of objects or lights against a contrasting background and in the presence of a given foreground brightness are provided in the present book. Variations in the visual-contact altitude and the slant visual range of the pilot have been analysed in detail for daylight, darkness and twilight.—(6.5).

ELECTRONICS

Operating characteristics of the four-loop VOR antenna in the 108-*Mc to* 112-*Mc band. W. L. Wright. C.A.A. Technical Development Report No.* 257 (*March* 1955).

This report supplements a previous Technical Development Report and describes the operation of the four-loop VOR antenna in the 108-Mc to 112-Mc band.—(11).

FUELS AND LUBRICANTS

Experiments with a rotating-cylinder viscometer at high shear rates. J. A. Cole et al. N.A.C.A., T.N. 3382 (*June* 1955).

Two straight mineral oils and a polymer-containing oil have been tested in a rotating-cylinder viscometer at high shear rates (maximum 0·25 million reciprocal seconds) and the accompanying heat effects have been investigated.—(14.2).

HYDRODYNAMICS

See also STRUCTURES: LOADS

Approximate hydrodynamic design of a finite span hydrofoil. A. N. Vladimirov. N.A.C.A. Technical Memorandum 1341 (*June* 1955).

Previous work on the motion of various bodies under the surface of a heavy fluid is discussed. The solution of the motion of a flat plate by Keldysh and Lavrentiev is applied to the motion of a hydrofoil, making possible the presentation of charts for determining the lift and resistance of an infinite span hydrofoil operating in a heavy frictionless fluid having infinite depth below the free water surface. Consideration is given to the effects of viscosity and a method is suggested to correct for the finite span.—(17.2).

LAW, REGULATIONS AND PATENTS

L'assicurazione aeronautica. B. de Mori. Centro Per Lo Sviluppo Dei Trasporti Aerei. No. 33 (*April* 1955).—(19).

MATERIALS

Contributions a l'étude de la déformation des métaux par chocs répétés. Y. Pironneau. O.N.E.R.A. Publication No. 75 (1955). —(21.0).

Effect of oxygen content of furnace atmosphere on adherence of vitreous coatings to iron. A. G. Eubanks and D. G. Moore. N.A.C.A., T.N. 3297 (*May* 1955).

A series of vitreous coatings of the same basic composition, but with cobalt-oxide contents varying from 0 to 6·4 per cent. by weight, was fired on ingot iron in atmospheres consisting of various oxygen-nitrogen mixtures. The effect of the oxygen content of the atmosphere on adherence was determined by subjecting each specimen to the American Society for Testing Materials adherence test, and the effect on interface roughness was estimated from examination of metallographic sections.—(21.4).

MATHEMATICS

L'interpolation idéale et son calcul numerique effectif. P. Vernotte. Publications Scientifiques et Techniques du Ministère de l'Air. No. 300 (1955).—(22.1).

On the practical solution of linear equations. B. Langefors, S.A.A.B., T.N. 35 (*November* 1954).

The use of inverse matrices is compared with the using of results from elimination work for obtaining solutions to systems of equations which have previously been solved for other right-hand members. Some procedures for approximately solving systems of equations and for iterative solutions are further discussed and a new approach to the solution of such equations, which may be established by the aid of matrix transformation, is suggested.—(22.1).

MECHANICAL ENGINEERING

Comparison of performance of experimental and conventional cage designs and materials for 75-*millimeter-bore cylindrical roller bearings at high speeds. W. J. Anderson et al. N.A.C.A. Report* 1177 (1954).

Studies are reported of four experimental bearings with outer race riding cages and inner race guided rollers operated at lower temperatures and to higher DN values (product of bearing bore in mm. and shaft speed in r.p.m.) than conventional inner and outer race riding cage-type bearings. (Formerly TN 3001; TN 3002).—(23.2.1).

Friction, wear, and surface damage of metals as affected by solid surface films. E. E. Bisson et al. N.A.C.A., T.N. 3444 (*May* 1955).

A summation is presented of N.A.C.A. results obtained from friction and wear investigations from 1946 to 1954. The results are consistent with theoretical predictions that solid surface films of low shear strength can serve to reduce both friction and surface damage.—(23.2.1).

POWER PLANTS

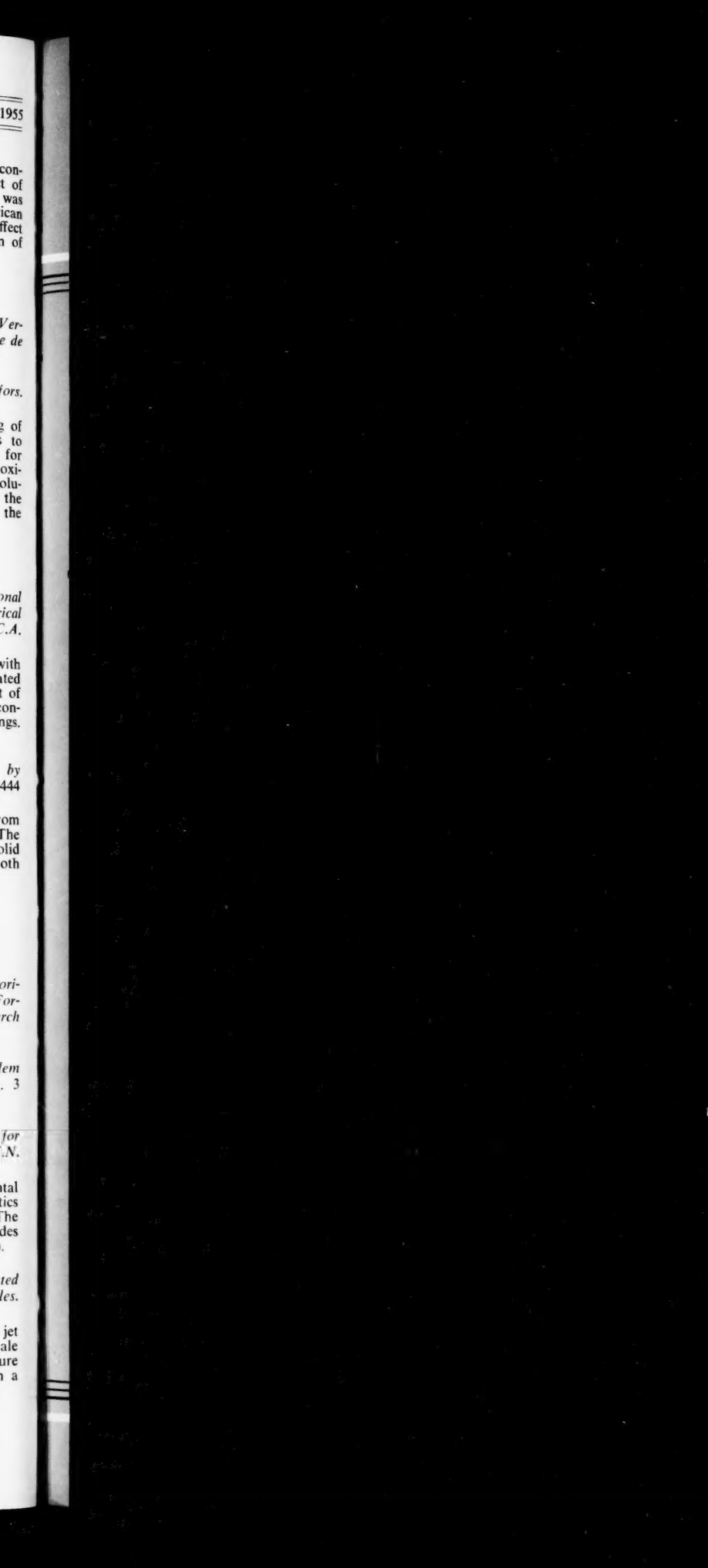
See also AERODYNAMICS: THERMO-AERODYNAMICS

Uber die Wirtschaftlichkeit von Wasserdampfraketen als Horizontal-Starthilfen. H. H. Kolle. Mitteilungen aus dem Forschungsinstitut fur Physik der Strahlantriebe E.V. No. 2 (*March* 1955).—(27.3).

Die Wege des Strahlfluges. E. Sanger. Mitteilungen aus dem Forschungsinstitut fur Physik der Strahlantriebe E.V. No. 3 (*June* 1955).—(27.3).

Design and performance of throttle-type fuel controls for engine dynamic studies. E. W. Otto et al. N.A.C.A., T.N. 3445 (*April* 1955).

The results are given of an analytical and experimental investigation of the steady-state and dynamic characteristics of three types of throttle-controlled fuel systems. The experimental results show that linearised analysis provides an adequate description of the dynamic response.—(27.1).

Investigation of jet-engine noise reduction by screens located transversely across the jet. E. E. Callaghan and W. D. Coles. N.A.C.A., T.N. 3452 (*May* 1955).

An investigation of screens located transversely across a jet as a noise-reduction device was conducted on a full-scale turbo-jet engine. The screens lowered the sound pressure levels rearward and increased them in front resulting in a nearly circular non-directional sound field.—(27.1).